A DYNAMIC DISTRIBUTION SYSTEM PLANNING MODEL CONSIDERING NON-WIRE ALTERNATIVES

BY

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This work is dedicated to my loving parents, wife, and daughter without whom after god’s help this work would not have been possible

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ABBRIVIATION

ADN : Active Distribution Network

AS : Ancillary Services

DER : Distributed Energy Resources

DP : Dynamic Planning

DSO : Distribution System Operator

DSP : Distribution System Planning

ESS : Energy Storage System

MCP : Market Clearing Price

NER : Network Expansion Planning

OM : Operating and Maintenance cost

RES : Renewable Energy Resources

INDICES, SUBSCRIPTS, AND SUPERSCRIPTS

t : Time in hour, t = 1,. . . ..,24.

d : Day, i = 1,. . . ...,D.

y : Years, y = 1,. . . ...,NY.

N : Number of buses in the system.

i, j, k : Bus number.

PARAMETERS AND CONSTRAINTS

π^{ISO} : Market clearing price (\$/MW) .

$\pi^{R}, \pi^{U}, \pi^{D}$: Price of reserve capacity, regulation up and down, respectively (\$/MW).

π^{L} : Bilaterally contracted price paid by the consumers to DSO (\$/MW).

L_{dt} : Load demand (MW).

C_{CAP}^{P} : Capital cost of power rating of ESS (\$/MW).

C_{CAP}^{E} : Capital cost of capacity of ESS (\$).

$C_{\min}^{P}$: OM cost of power of ESS (\$/MWh).

$C_{\min}^{E}$: OM cost of capacity of ESS (\$/MWh).

$BatC$: The cost of battery replacement(\$/MWh).

DC : Discharging cost of ESS (\$/MWh).

η : Efficiency of charging/discharging of ESS.

C_{CAP}^{pv} : Capital cost of solar (\$/MW).

$C_{\min}^{pv}$: OM cost of solar (\$/MW).

p_{dt}^{pv} : Power output of PV (MW).

C_{CAP}^{wt} : Capital cost of wind ($/MW).

$C_{\min}^{wt}$: OM cost of wind ($/MW).

p_{dt}^{wt} : Power output of WT (MW).

C_{CAP}^{TG} : Capital cost of thermal generator ($/MW).

$C_{\min}^{TG}$: OM cost of thermal generator ($/MW).

Γ : Upper limit of block of piecewise linear cost of thermal unit.

A_{TG} : Coefficient of the piecewise linear production cost of thermal unit.

F_{TG} : Slope of a segment of the piecewise linear cost function.

FC_{TG} : Fuel cost.

A_g, B_g, C_g : Coefficients of quadratic of thermal cost function.

C_{CAP}^{UL} : Capital cost of adding new line ($/MW).

C_{CAP}^{NL} : Capital cost of upgrading existing line ($).

r : Discount rate.

Y_{com}^{n} : The lifespan of the component in years.

DECISION AND AUXILIARY VARIABLES

TP : Total profits ($) .

SV : Salvage value of all resources at end of planning horizon ($).

TI : Total Investments cost ($).

AP : Annual profits ($).

C_{INV}^{P} : Calculating investment cost of power rating of ESS ($/MW).

C_{INV}^{E} : Calculating investment cost of capacity of ESS ($).

MP_{yk} : Sizing power rating of ESS in each bus.

ME_{yk} : Sizing capacity of ESS in each bus.

ESS_{dt} : The charging/discharging of ESS (MW).

GG_{dt} : Energy depreciation cost.

SOC_{dt} : State of charge (MWh).

C_{INV}^{PV} : Calculating solar investment cost ($).

N_{yk}^{PV} : The Sizing of solar in each bus (MW).

C_{INV}^{WT} : Calculating wind investment cost ($).

N_{yk}^{WT} : Sizing of wind in each bus (MW).

C_{INV}^{TG} : Calculating TG investment cost ($).

N_{yk}^{TG} : Sizing of thermal generator in each bus (MW)

u_{yk}^{TG} : Initial state of thermal generator.

P_{yk}^{TG} : Output power of thermal generator (MW).

δ : Power output corresponding to a segment of a piecewise linear cost function.

C_{INV}^{NL} : Calculating investment cost of adding new lines ($/MW).

C_{INV}^{UL} : Calculating investment cost of upgrading existing lines ($).

BID_{ydt} : Amount of bid (MW).

E_{dt} : Production Cost of conventional generator ($/MW).

V, θ : Voltage magnitude and phase angle.

P_i, Q_i : Real and reactive power at bus i.

R^R, R^U, R^D : Bid of reserve capacity, regulation up and regulation down, respectively (MW).

ABSTRACT

Full Name : [ADNAN SALMAN NASSER ALBUKHAYTAN]

Thesis Title : [Hybrid Dynamic and Linear Planning Model of Distribution Resources for Energy and Ancillary Services Participation]

Major Field : [ELECTRICAL ENGINEERING]

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As the increasing growth in electrical demand year after year and because of the limited natural resources, utilization of clean renewable energy resources (RESs), such as photovoltaics PV and wind turbine are required. Moreover, the environmental concerns have increased over past years. Thus, many governments have started to formulate renewable policies and standards to promote generation from RESs to maintain natural resources and environment. In addition, many current regulations allow distribution companies to interact with the grid with a few requirements. Thus, distribution companies are able to buy/sell energy from/to the grid and provide ancillary services (AS) to the grid such as frequency regulation and reserve services. A proper planning for a distribution companies willing to serve its local load, buy/sell energy and provide AS could be a challenge.

This research proposes a dynamic planning model used by a distribution system operator (DSO) to maximize long term profits. The distributed energy resources (DERs) include renewable resources (RESs), thermal generators (TGs), and energy storage systems (ESS). The primary motivation is to find the optimal sizing and location of DERs with considering network expansion planning (NEP) that maximizes the total expected profits. In addition, The DSO trades energy externally with the system operator at the market-clearing price (MCP) and internally with its consumers at a fixed price. Moreover, the DSO participates in the ancillary services (AS) market and provide AS to the grid. The option for maximizing the DSO's long-term payoffs is analyzed by considering the investment and maintenance costs of DERs and NEP as well as the degradation of ESS due to cycling. A complete AC power flow calculation requires a significant amount of computing resources. Thus, linear power flow equation are used to address the network constraints (voltages, thermal line limits). In addition, linear programs are used to optimize buying/selling energy from/to grid and participating in AS market by reflecting all prices to the present worth.

There are many uncertainties in the system such as renewable resources power output, MCP, and load. To reduce the size of the problem, wind turbine (WT) power output and MCP uncertainties are considered, and the two-stage stochastic programming methodology is employed to cope with these uncertainties. The proposed model is formulated as a mixed-integer stochastic linear program. The proposed model's performance has been investigated with the aid of a case study based on a 38-bus radial distribution test system. To demonstrate the effectiveness of the proposed model, real data for load profile, WT power output and MCP are obtained from the Electric Reliability Council of Texas market (ERCOT). Simulation results show the optimal location and sizing of DERs and selected added/upgraded lines to the network to maximize the total profits to the DSO.

ملخص الرسالة

الاسم الكامل: عدنان سلمان ناصر البخيتان

عنوان الرسالة:

التخصص: هندسة كهربائية

تاريخ الدرجة العلمية: أبريل ٢٠٢١

نظرًا للنمو المتزايد في الطلب على الكهرباء عامًا بعد عام وبسبب الموارد الطبيعية المحدودة ، فإن استخدام موارد الطاقة المتجددة النظيفة: مثل الخلايا الكهروضوئية وتوربينات الرياح مطلوب. علاوة على ذلك، ازدادت المخاوف حول البيئة خلال السنوات الماضية. لذالك، بدأت العديد من الحكومات في صياغة سياسات ومعايير متجددة لتعزيز التوليد من مصادر الطاقة المتجددة للحفاظ على الموارد الطبيعية والبيئة. بالإضافة إلى ذلك، تسمح العديد من اللوائح الحالية لشركات التوزيع بالتفاعل مع الشبكة مع بعض المتطلبات. وبالتالي، فإن شركات التوزيع قادرة على شراء / بيع الطاقة من / إلى الشبكة وتقديم الخدمات الإضافية (AS) للشبكة مثل تنظيم التردد وخدمات الاحتياطي. التخطيط المناسب لشركات التوزيع الراغبة في خدمة حمولتها المحلية وشراء / بيع الطاقة وتوفير AS يمكن أن يكون تحديًا.

يقترح هذا البحث نموذج تخطيط ديناميكي يستخدمه مشغل نظام التوزيع لتحقيق أقصى قدر من الأرباح على المدى الطويل. تشمل المصادر المتجددة والمولدات الحرارية وأنظمة تخزين الطاقة. الدافع الأساسي هو إيجاد أفضل حجم وأفضل موقع لمصادر الطاقة المتجددة والمولدات الحرارية وأنظمة تخزين الطاقة مع أخذ بالاعتبار تخطيط توسيع الشبكة الذي يزيد من إجمالي الأرباح المتوقعة. بالإضافة إلى ذلك، يتاجر DSO بالطاقة خارجيًا مع مشغل النظام بسعر السوق (MCP) وداخليًا مع المستهلكين بسعر ثابت. علاوة على ذلك، يشارك مشغل نظام التوزيع في سوق الخدمات المساعدة (AS) ويوفر AS للشبكة. يتم تحليل خيار تعظيم المكاسب طويلة الأجل لـ مشغل نظام التوزيع من خلال النظر في تكاليف الاستثمار والصيانة لـ المصادر المتجددة والمولدات الحرارية وأنظمة تخزين الطاقة وتوسيع الشبكة. تُستخدم معادلات تدفق الطاقة الخطية لمعالجة قيود الشبكة (الفولتية، حدود الخط الحراري).

بالإضافة إلى ذلك، تُستخدم البرامج الخطية لتحسين شراء / بيع الطاقة من / إلى الشبكة والمشاركة في سوق AS من خلال عكس جميع الأسعار إلى القيمة الحالية.

هناك العديد من أوجه عدم اليقين في النظام مثل إنتاج الطاقة المتجددة، وسعر الطاقة في السوق، والحمل. لتقليل حجم المشكلة، يتم أخذ ناتج طاقة توربينات الرياح وسعر الطاقة في السوق في الاعتبار ويتم استخدام منهجية البرمجة العشوائية ذات المرحلتين للتعامل مع حالات عدم اليقين هذه. تمت صياغة النموذج المقترح كـ MIP. لإثبات فعالية النموذج المقترح، يتم الحصول على بيانات حقيقية لملف تعريف الحمل وإنتاج الطاقة المتجددة وسعر الطاقة في السوق من مجلس الموثوقية الكهربائية لسوق تكساس (ERCOT). تُظهر نتائج المحاكاة إيجاد الحجم الأمثل وأفضل موقع لمصادر الطاقة المتجددة والمولدات الحرارية وأنظمة تخزين الطاقة مع أخذ بالاعتبار تخطيط توسيع الشبكة لزيادة إجمالي أرباح لمشغل شبكة التوزيع.

CHAPTER 1

INTRODUCTION

1.1 Background and Problem Description

The penetration of RESs have been grown dramatically over the past years because of environmental concerns and the limited natural resources. The accumulated capacity of global PV power increased from 41 GW in 2010 to 486 GW in 2018, while the wind power increased from 180 GW in 2010 to 564 GW in 2018 [1].

Recently, many power system regulators have pushed system planners to use non-wire alternatives (NWAs) approach instead of the traditional approach to meet demand growth [2]. The definition of NWAs is to consider distribution energy resources, demand response and dynamic pricing to delay or substituted for the installation of more conventional 'wires and poles' infrastructure [3].

RESs are not controllable and performance of RESs depends strongly on the weather conditions. In addition, the RESs are usually distributed and independently controlled. However, the traditional power system is controllable and centralized. Therefore, adapting RESs to grids introduce new technical, quality and protection challenges to the system. [4], [5].

The RESs are stochastic in nature, variations in RESs output may cause heavily ramifications on the grid [6], [7], [8]. Several authors have proposed to overcome this challenge by incorporating ESS [9], [10], [11]. The purpose of ESSs is to charge/discharge the energy to mitigate the surplus/deficit energy generated by RESs.

ESS technology helps only to alleviate the variations of RESs to a certain extent. Thus, the variations of RESs output needed to be incorporated in the proposed model to improve the planning efficiency. Researchers have suggested several methodologies to mitigate the effects of the uncertain parameters in the power system. In [12], [13], [14], [15] two stage stochastic models have been developed to optimally incorporate uncertainty into the power system planning problem. In [15], the model is formulated as a mixed-integer stochastic linear program where planning variables are made in the first stage and scenario-dependent operation decisions are done in the second stage.

The DSO is to maximize its payoffs while complying with operational and contractual constraints. Therefore, an optimal model for distribution system planning (DSP) and operating of DERs in electricity markets is important. The optimization of the operation process determines the DSO's optimal hourly bidding and offering strategies to maximize DSO's payoffs.

There are two methods proposed for solving the ADN problem which are static planning (SP) [16] and dynamic planning (DP) [17]. Although the dynamic planning method increases the complexity of the problem, it helps the DSO in two main aspects that are technical responses and investment savings. The static planning method determines the optimum location and size of the DERs at the beginning of the project. However, the dynamic planning method not only determines the optimal location and size of DERs, but also the optimum time to invest. Thus, in the dynamic planning, the investment is distributed optimally over the planning time horizon, while in the static planning, the entire investment takes place at the beginning of the planning time horizon.

The salvage value of the asset is subtracted from its original cost to calculate the total depreciation over the asset's useful life [18], [19]. It is more efficient to introduce salvage value of the DERs and the network expansion planning (NEP) in dynamic planning than in static planning as the salvage value is highly dependent on the useful life of assets. In the static planning method, the investment will be made at the beginning of the project, so that the useful life of the assets will be reduced at the end of project, which will lead to a dramatic reduction in the salvage value of the assets. However, in the dynamic planning, the investment does not always have to be made at the beginning of the project, it depends on the optimization model with taking into account the salvage value of the assets.

1.2 Ancillary Services (AS)

It is well known that the supply must equal the demand at every moment and the power system operator needs to make adjustments every single moment as demand and RESs power output change. Most of these adjustments are automatic responses using a huge network of sensors in the power grid.

The DSO buy/sell energy from/to day-ahead market to meet the anticipated demand requirements. DSO does the same way on an hour-ahead time market frame. However, the load is increasing/decreasing each moment and DSO needs to cope with these changes.

One of the proposed solutions to cope with these changes is to provide AS. The AS can be defined as the functions that help the system operator to maintain the reliability and stability of power system. AS can be used to maintain the balance between the supply and demand, continuity of the power flow in the grid and help the power system to black start after a power system event. Moreover, with significant penetration of RESs, additional AS are required to manage the variability and uncertainty of these resources. AS includes synchronized regulation (the ability to make correction for a short-term change in imbalance between load and generation that might affect the stability of the system), black-start regulation (the ability to restart a grid after unlikely event blackout), and contingency reserves (the ability to respond to an expected failure or outage of a system component) [20], [21]. There are different methodologies to provide AS to the grid including demand response, frequency response and ESS. There are pros, cons and respond time of each mentioned methodology [22].

Due to the fast response of ESS, it is used to provide AS including reserve services and frequency regulation to the grid to maintain the stability and reliability [23], [24], [25]. Thus, the planning of ESS to find the optimal location and sizing to provide AS is crucial and must be included in this research work.

1.3 Energy and Power Markets

In order to comprehend the difference between wholesale energy markets and traditional financial markets, it is necessary to understand the nature of electricity trading. The electricity is produced and consumed instantaneously, so that supply and demand must be constantly balanced in real-time. The day-ahead and real-time markets are managed and operated by Independent System Operators (ISOs)/ Regional Transmission Organizations (RTO). These ISOs/RTOs are not-profits entities and they are responsible to ensure the reliability and stability of energy and AS services market.

There are currently seven ISO in the United State of America. In these seven markets, the DSO can participate in electricity market to buy/sell energy from/to the grid as well as participate in AS markets to provide AS including Regulation, Spinning Reserves and Non-Spinning Reserves.

The market data used in this is collected from Electricity Reliability Council of Texas (ERCOT). ERCOT operates the electric grid and manages the deregulated market for 75 percent of the Texas State. In day-ahead market, ISO provides a forward energy market for participants. Then, electricity generators and load serving entities submit their bids to ISO either buying or selling energy in hourly basis. After that, ISO runs its own optimization considering transmission/distribution constraints, cost and security. Finally, the selected market participants will commit to the schedule with the market clearing price (MCP). In AS market, the ISO conducts AS plan and provides AS information that identifies required capacities and the prices in hourly basis in day-ahead. After that, each participant should submit its bids for providing AS to ISO including capacity in hourly basis. After that, the ISO run its own optimization considering transmission/distribution constraints and security. Finally, the ISO post the accepted bids. In real-time, signal defining the needed percentage from the total bided capacity is sent to the accepted bids participant. The process for energy and AS markets are shown in the Figure 1.1. Table 1.1 summarizes the energy and AS provided by ERCOT [26].

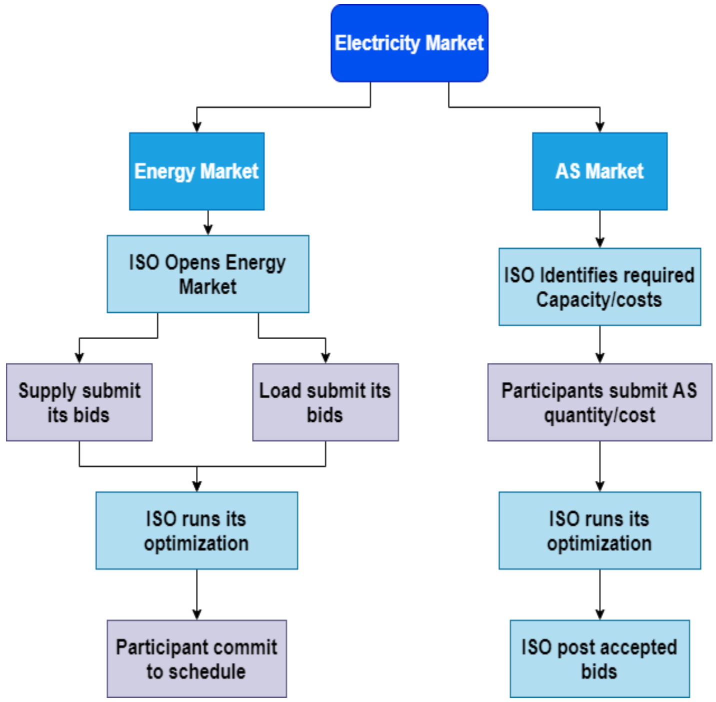

Figure 1.1: Electricity market

Table 1.1: Energy and AS description

Product	Description
Electric Energy	Submitted either to buy/sell energy in day-ahead
Regulation UP	Immediate response is required to decrease the power output to response to deployment signal.
Regulation Down	Immediate response is required to increase the power output to response to deployment signal.
Responsive reserves	Required to respond to the signal within few minutes.
Non spinning reserves	Required to respond to the signal less than 30 minutes and run for a minimum an hour

1.4 Research Objective

The main objective of this thesis is to propose a dynamic planning (DP) model that assists the DSO who would like to invest in ADN for maximizing the profits. The model incorporates the optimal location and sizing of DERs with NEP. The DERs includes in this research are thermal generator, solar PV, wind turbine, and ESS. The network expansion-planning model considers adding new lines to the existing network and/or upgrading existing lines.

The DSO participates in energy and AS markets. In the energy market, the DSO trades energy externally with the system operator at the MCP and at a fixed price with local loads. In AS market, the DSO uses ESS to participate in AS market to provide regulation up/down and reserve to the grid. The main motivation of this research is to find the optimal sizing and location of DERs with considering network expansion planning that maximizes the total expected profits to the DSO.

The milestones of this research are the following:

- A dynamic planning model that assists the distribution system operator who wants to invest in an active distribution network to serve specific local load and participate in the electricity and AS market.
- This model aims to demonstrate the feasibility of the investment in the ADN by deciding the optimal sizes and locations of the different available resources (namely PV, WT, TGs, and ESS) and obtaining the optimal profits during the studied period.
- The ESS is used to participate in the energy and AS market by bidding regulation up/down and reserve capacities considering the different ESS's physical constraints.
- The whole model is developed as a linear model and integrated with linear Power flow equations to address the network constraints (voltages, thermal line limits), to find the optimum location and sizing of DERs and to add/upgrade new/existing lines.
- The model provides the ability to incorporate the effects of regulation capacities and signals in the network voltages and lines limits.
- The uncertainties associated wind and market prices (MCP) are handled using two stage stochastic programming. However, PV and load are assumed to be deterministic because

demand and PV output are predictable. The purpose of not considering PV and load is to minimize the size of the problem.

1.5 Approach

In order to achieve the research objectives, the work will be broken into steps as following:

1. Optimal planning model to find the optimal sizing of DERs is formulated.
2. Incorporating the linear model of the distribution model to include network constraints. Then, the optimal location and sizing of DERs are taken into account.
3. Integrating NEP to add/upgrade new/existing lines to enhance existing network. Binary decision variables are used to decide to add/upgrade lines.
4. Incorporating AS to the grid and participating in AS market including regulation up/down and reserve requirements.
5. Formulating the whole model as a dynamic model find the optimal location and sizing of DERs a well as the best time to install them.
6. Deciding in the uncertain parameters and the model as a mixed integer two stage stochastic linear programming model.

CHAPTER 2

LITERATURE REVIEW

2.1 NEP

Researchers in [33], [34], and [35] focused mainly on NEP to minimize the overall cost. In [33], a two-stage stochastic mixed-integer Second-order conic programming model has been used for NEP. Reference [33], [34] proposed a multi-objective framework for DSP to minimize total cost and profits at risk. In [35], an optimal planning approach to find the optimal NEP and reinforcement was discussed. Besides, existing DGs were considered to provide AS to the network. However, researchers in these papers [33],[34], and [35] considered only NEP in their work without addressing DGs and ESS in their model. References [33], [34] have not addressed AS in their work. Authors in [35] have considered a nonlinear model to handle NEP

2.2 ESS Planning

A planning model that incorporated ESS with NEP in ADN was discussed in papers [36][37], [38], and [39]. In [36], a methodology was proposed to find the optimal location, capacity, and power rating of ESS. The optimal sizing and location of ESS in ADN minimizing the investment cost, voltage magnitude deviation, and feeders'/lines' congestion was proposed in [37]. Both [36], and [37] addressed the ESS planning model that integrated with the operation of RESs. However, NEP and planning DGs have not been considered in [36], [37]; the planning were done only for ESS. In addition, AS has not been considered in [36] and [37].

The ADN planning aims to minimize the overall costs for feeders' investment, ESS investment, and other operational costs was discussed in [38]. The decision variables include the location and type of feeders and the ESS for a given planning horizon. A planning process for NEP and ESS involved comparing several feasible plans for optimization costs was addressed in [39]. The costs include the cost of new assets and their replacements, operation, and maintenance costs, as well as reliability costs. However, a nonlinear model was addressed in [38], [39]. Moreover, they have addressed NEP and ESS, but DGs were not considered in their work.

2.3 DGs Planning

Researches in [40], [41], [42], [43] and [43] [44] have addressed DGs in ADN planning. In [40], Network expansion planning and optimal sizing and location of the thermal generator have been obtained using an optimization model to maximize the distribution companies' profits. A novel model to solve the DG locating and sizing in AND, including network reconfiguration, to minimize the overall cost has been introduced in [41]. In [42], the authors propose a model to find the optimal siting and sizing of RESs in ADN to minimize the overall cost, including the investment, operation, and maintenance costs. A planning model obtains optimum wind turbine (WT) and photovoltaic (PV) size and location based on existing DGs in the distribution system while reducing both active and reactive power losses as well as voltage deviations was addressed in [43]. A model to find the optimal sizing of RESs to minimize the long-term cost including investment cost and operating cost was discussed in [44]. However, researchers in [40], [41], [42], [43], and [44] addressed a nonlinear model and they have not included AS in their work. Moreover, NEP was not considered in [41], [42], [43], and [44]; they did planning only for DGs.

A planning model incorporating DGs with NEP has been addressed in [45], [46], [47], and [48]. In [45], authors proposed multi-objective functions for DEP. The objective function of the upper-level problem is to minimize generation and network investment costs while meeting demand. The objective function to be considered at a lower level is to minimize the total payment that consumers have to afford over a given time horizon. In [46], the researchers introduced a novel model for the problem of multi-stage DEP, which can jointly extend both NEP and DERs with linearize AC power flow equations. In [47], the authors proposed a bi-level planning model was proposed where the optimal locating and sizing of RESs made in the first stage and then incorporating DSTATCOM with RESs in the second stage. Researchers in [48] proposed a mixed-integer linear stochastic model to incorporate NEP with optimal planning for RESs and thermal generator to minimize the total investment and operating costs. However, ESS and AS were not taken into account in [45], [46], [47], and [48].

2.4 ESS incorporated with DGs Planning

Researchers in [49], [50], [51], and [52] proposed a planning model that incorporated ESS and DGs in ADN planning. In [49], the authors introduced a planning model to find the optimal location and sizing of ESS and DGs in the distribution system. The objective function was to minimize the overall cost, including annualized investment cost, expected revenue (cost) in the day-ahead market, and the imbalance cost in the real-time market. ADN planning model for multi-type distributed generation and ESS is discussed in [50]. The proposed model's purpose was to identify the optimal sizing and location of ESS, WT, and PV to maximize the net present value to DSO. In [51], the optimal location and sizing of DGs to provide ancillary services were discussed. In [52], the authors addressed a mixed-integer conic programming model (MICP) to find the optimal location and sizing dispatch/non-dispatch generators and ESS with considering NEP. In addition, they have used dynamic and linear model in their work. Nevertheless, the market environment and AS were not addressed in their model. A nonlinear model and static planning were approached in [49], [50], and [51]. Moreover, authors in [49] and [50] did not consider AS into their model.

2.5 Stochastic Programming

Stochastic programming (SP) is the model familiar approach applied in different areas in power system to handle stochastic parameters [1]. The SP approaches have been applied in power system in short-terms operation [2], [3], and [4]. In [2], [4], a two stage SP is used to handle WT power output in ADN. In [2], the WT power was dispatched the first stage and then the recourse cost and operational risk were addressed in the second stage. In [4], the SP is used to handle WT power output variation drive the optimal operation to maximize the profits. A stochastic mixed integer linear programming was proposed to evaluate the impact related wind intermittency generation and ESS in DSO on the economic dispatch.

In addition, the SP approaches have been applied in power system in long-term planning [5], [6], [7], [8], and [9]. A mixed integer liner programming model for a long-term and large-scale generation expansion planning was proposed in [5]. The SP was used to handle the variation of large amount of WT power output. In [6] and [7] the SP was used to handle the load uncertainty.

In [6], a long-term reactive power planning was addressed to minimize the investment costs as well as operation costs. A co-planning of gas and power networks was introduced to minimize the total costs including investment costs and operation costs were discussed in [7]. In [8], the concept of SP was used to optimize the sizing of ESS to provide ancillary services to maximize profits.

Ancillary services (AS) are connected to the services provided by the grid to ensure continuity in the power flow of the grid and to guarantee reliability of the electrical network [27] and [28]. Most of the researchers consider ESS to participate in AS [29], [30], [31], and [32]. A few of them have considered DGs and ESS to provide ancillary services.

To summarize the literature survey, Table 2.1 shows the outline review of the published papers on the of ADN planning. The papers are evaluated in a variety of ways and a complete comparison is carried out.

Table 2.1: Outline study of researches in ADN planning problem

Ref	Year	DERs Planning	AS	DP	NEP	Linear	ME
[33]	[2017]	-	✗	✗	✔	✔	✗
[34]	[2015]	-	✗	✗	✔	✔	✔
[35]	[2017]	-	✔	✗	✔	✔	✗
[36]	[2016]	ESS	✗	✗	✗	✗	✔
[37]	[2018]	ESS	✗	✗	✗	✔	✔
[38]	[2019]	ESS	✗	✔	✔	✗	✔
[39]	[2018]	ESS	✗	✔	✔	✗	✗
[40]	[2019]	TG	✗	✔	✔	✗	✔
[41], [42]	[2017] [2018]	PV + WT + TG	✗	✗	✗	✗	✔
[44]	[2019]	PV + WT	✗	✗	✗	✗	✔
[45]	[2017]	PV + WT	✗	✔	✔	✔	✔
[46]	[2018]	WT + TG	✗	✔	✔	✔	✔
[47]	[2019]	WT + PV	✗	✗	✔	✗	✔
[48]	[2018]	WT + PV + TG	✗	✔	✔	✔	✔
[49]	[2018]	WT + TG + ESS	✗	✗	✗	✗	✔
[50]	[2019]	PV + WT + ESS	✗	✗	✗	✗	✔
[51]	[2019]	TG + PV + WT + ESS	✔	✗	✔	✗	✔
[52]	[2020]	TG + PV + WT + ESS	✗	✔	✔	✔	✗
Proposed	[2021]	TG + PV + WT + ESS	✔	✔	✔	✔	✔

AS: Ancillary Services　DP: Dynamic Planning　NEP: Network Expansion Planning　ME: Market Environment

2.6 Gaps in the literature and contribution

As seen from the literature, most published papers have considered the static planning framework incorporating RESs, TG, and ESS. The optimal sizes and locations of the different available resources (namely PV, WT, TGs, and ESS) are considered in the proposed model. In addition, the annual growth of load and annual installation of DERs are not considered in static planning approach as explained in Section 1.1. However, in this research work, a dynamic planning approach to find the optimal time to install DERs with considering the annual load growth.

Many researchers proposed to enhance the network by considering only reinforcing/upgrading existing lines rather than adding new lines. However, in the proposed model enhancing the network considers both upgrading existing lines and also adding new liens the network.

In the case of ADN planning, most of the research focused on using a nonlinear network model, which makes it difficult to be solved in a large system. In this research, the whole model is developed as a linear model and integrated with linear power flow equations to address the network constraints to find the optimum location and sizing of DERs and to enhance the distribution network.

A very limited number of researchers considered investing in ESS with RESs to maximize profits and participate simultaneously in the AS market. However, the ESS is integrated with RESs to overcome the challenges caused by RESs. In addition to that, the ESS is also used to participate in energy and AS markets to maximize the profits to DSO.

In the case of bidding regulation capacities to the market, most of the paper ignoring the effect of regulation signal on the network limits. The proposed model provides the ability to incorporate the effects of regulation capacities and signals in the network voltages and lines limits.

CHAPTER 3

DSO PLANNING MODEL ENERGY AND ANCILLARY SERVICES PARTICIPATION

This chapter will discuss the deterministic optimization of DSO as a linear model to participate in energy market. The DSO model is described and formulated as a linear model to find the optimal sizing of DERs where the objective of the model is to maximize the total payoffs to the DSO.

3.1 DSO Planning Model

The active distribution networks (ADN) planning model in this research work considers the total investment cost (TI) of DERs including thermal generators (TG), photovoltaic (PV), wind turbine (WT) and energy storage system (ESS). Moreover, the annual maintenance costs of the DERs are also taken into account. The investment cost represents the cost of procuring the power capacities of TG, PV, WT and ESS.

Figure 3.1 shows the system model of ADN. The DSO would like to buy/sell energy from/to the external wholesale energy market at the market clearing price (MCP) on a day-to-day basis to maximize payoff and to serve its loads at a fixed price. The optimal bidding/offering to/from the electricity market is determined by the proposed model to maximize profits on a daily basis.

In order to develop its optimum bids, the DSO predicts the hourly load of its consumers and the power output of DERs. After that, an external market optimization is carried out by the DSO to submit the hourly optimal energy bids to the external market in day-ahead bases.

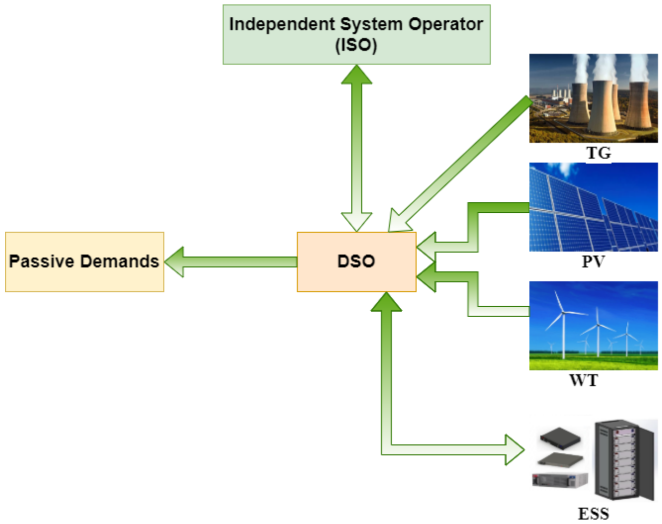

Figure 3.1: System model without AS

In this model, the ESS is used for two purposes. The first purpose is to maximize the profits to ADN and the second one is to overcome the challenges caused by the intermittent of the RESs. When RESs produces more/less than expected, the ESS shall be charged / discharged to avoid penalties.

In fact, the ESS is sufficient to maximize profits for the ADN. ESS is involved in storing energy during light loading periods on the system and delivering it during periods of high demand. During peak demand periods, the ESS delivers power to the wholesale market at a high price. However, during periods of off-peak demand, the ESS charges power from the production of DERs and/or buy energy from the wholesale market at low price.

3.2 Problem Formulation

In this section, the deterministic optimization model of ADN to participate in energy market is formulated to maximize the total payoff to DSO. It is assumed that the DSO intends to participate in a pool-based market. It is expected to submit energy bids to the day-ahead market, selling/buying energy to/from the wholesale market. Each bid is to be cleared in its concerned pool-based market mechanism. In the coming section, the model is distributed into planning section and into operation section for the purpose of explanation. However, the planning and operation models are solved simultaneously.

3.2.1 Planning Optimization Model

The proposed model of this research work is from DSO's perspective. Thus, maximizing the profits of the ADN is considered to be the most important objective in this research work. It is also assumed that the DSO is the owner of the ADN's resources. The objective of this research is therefore to maximize revenue and minimize the overall cost as described in (3.1).

Maximize:

$$\text{TF=AP + SV - TI} \tag{3.1}$$

Where AP, TI and SV are annual profits, total investment costs and salvage value, respectively. Mathematically, AP, TI and SV have been defined in (3.2), (3.3) and (3.8), respectively. Total profits (TF) after a certain number of years, taking into account the salvage value of assets at the end of planning horizon and the total investment cost of ADN's resources is defined in (3.3). If TF is positive that means the investor makes profits from investing in ADN, otherwise the investor does not recover its investment cost in AND.

$$AP = \sum_{y=1}^{NY} (1+r)^{-y} (DF - N_y^{PV} C_{min}^{PV} - N_y^{WT} C_{min}^{WT} - N_y^{TG} C_{min}^{TG} - ME_y C_{min}^{E} - MP_y C_{min}^{P}) \tag{3.2}$$

Equation (3.2) helps the investor measures the profits on an annual basis, taking into account the discount rate (r) and the maintenance cost DERs. The first term (DF) in equation (3.2) is used to determine the daily profits to DSO. N_y^{PV}, N_y^{WT} and N_y^{TG} are the optimal sizing of PV, WT and TG, respectively. $C_{\min}^{PV}, C_{\min}^{WT}$ and $C_{\min}^{TG}$ are the capital maintenance costs of PV, WT and TG. The energy capacity and power rating of ESS are ME_y and MP_y, respectively. $C_{\min}^{E}$ and $C_{\min}^{P}$ are the capital maintenance costs of energy capacity and power rating ESS, respectively. Thus, the second, third, fourth, fifth and sixth terms in equation (3.2) are used to calculate the maintenance costs of PV, WT, TG and ESS, respectively.

Besides, there are four main components, namely thermal generator (TG), solar photovoltaic system (PV), wind turbine (WT), and energy storage system (ESS). Equation (3.3) determines the total investment costs (TI) of DERs

$$TI = (C^{PV} + C^{WT} + C^{ESS} + C^{TG})_{INV} \tag{3.3}$$

Equations (3.4), (3.5) and (3.6) are used to determine the investment cost of TG, PV and WT, respectively.

$$C_{INV}^{TG} = N^{TG} C_{CAP}^{TG} \tag{3.4}$$

$$C_{INV}^{PV} = N^{PV} C_{CAP}^{PV} \tag{3.5}$$

$$C_{INV}^{WT} = N^{WT} C_{CAP}^{WT} \tag{3.6}$$

Where N^{TG}, N^{PV} and N^{WT} are the decision variables used to determine the optimal capacity of TG, PV, and WT, respectively. Where $C_{CAP}^{TG}, C_{CAP}^{PV}$ and C_{CAP}^{WT} are the capital cost of TG, PV, and WT, respectively.

Equation (3.7) is used to calculate the investment cost of ESS. MP and ME are decision variables are used to find the optimal sizing of power rating and energy capacity of ESS, respectively. Where C_{CAP}^{P} and C_{CAP}^{E} are the capital cost of power and energy of ESS, respectively.

$$C_{INV}^{ESS} = C_{CAP}^{P} \cdot MP + C_{CAP}^{E} \cdot ME \tag{3.7}$$

Salvage value is used for properties with longer lifespans than the planning period. The salvage value is calculated based on the work presented in [57]. Equation (3.8) helps the DSO to calculate the salvage value of the assets with considering the installation time of the assets.

$$SV = \sum_{n=1}^{Type} SF(N^{n} C_{inv}^{n} \frac{Y_{rem}^{n}}{Y_{com}^{n}}) \tag{3.8}$$

SF is the salvage factor and $N^{n} C_{INV}^{n}$ is used to calculate the investment cost of each type of resource namely (TG, WT, PV and ESS). However, Y_{com}^{n} and Y_{rem}^{n} are the lifetime of the component and the remaining lifetime of the component in years, respectively.

The decision variables of the proposed model for the planning optimization model are summarized in the table below.

Table 3.1: Optimal planning variables and functions

Variable	Function
TF	Total profits
AP	Annual profits
SV	Salvage value
$C_{INV}^{TG}, C_{INV}^{PV}, C_{INV}^{WT}$	Investment cost of TG, PV and WT, respectively
N^{TG}, N^{PV}, N^{WT}	Sizing of TG, PV, and WT, respectively
C_{INV}^{ESS}	Investment cost of ESS
ME, MP	Energy sizing and power capacity of ESS, respectively

3.2.2 Operation Optimization Model

The expected daily profits for DSO is given in (3.9). K_d is the scaled weighted factor for days. The first term is the BID, which is submitted to the wholesale market to buy/ sell energy at MCP. The second term is the income from selling energy to consumers "local loads". The third and fourth terms are used to calculate the operation cost of thermal generator and the depreciation cost of ESS, respectively.

$$DP = \sum_{d=1}^{D} \sum_{t=1}^{T} K_d \cdot (\pi^{ISO} BID + \pi^{L} L - E - GG)_{dt} \tag{3.9}$$

Equation (3.10) ensures the balance between the total generation and demand at each hour. The term BID is assumed to be positive/negative if DSO decide to sell/buy energy to/from the wholesale market.

$$N^{PV} P_{dt}^{PV} + N^{WT} P_{dt}^{WT} + N^{TG} P_{dt}^{TG} = BID_{dt} + L_{dt} + ESS_{dt} \tag{3.10}$$

Equation (3.11) shows that the ESS depreciation cost GG is positive only when the ESS is discharged as discussed in [58]. Otherwise, it’s zero. Using ESS as charging/discharging to maximize the profits reduces the lifetime of ESS due to the increased cycling. Additionally, this deterioration is also affected by the current discharge level and current SOC at the time of discharge. The average cost per MW is calculated in (3.12), where the battery cost in this paper is normalized to the cost used in reference [58] by dividing by $BatC_{ref}$

$$GG_{ydt} = max\,(-DC \cdot ESS_{ydt} \cdot \eta^{Dis}, 0) \tag{3.11}$$

$$DC = 0.042\left(\frac{BatC}{BatC_{ref}}\right) \tag{3.12}$$

Inequalities (3.13) and (3.14) shall be used to specify the maximum power rating and energy capacity limits, respectively.

$$\underline{MP} \le ESS_{dt} \le \overline{MP} \tag{3.13}$$

$$\xi\underline{ME} \le SOC_{dt} \le \xi\overline{ME} \tag{3.14}$$

Equations (3.15) is the SOC of the ESS as it is charged/discharged.

$$SOC_{dt} = SOC\,(d,t-1) + ESS_{dt} \tag{3.15}$$

The limit of the minimum and maximum output of the traditional generator is set out in (3.16).

$$\underline{P^{TG}} \le P_{dt}^{TG} \le \overline{P^{TG}} \tag{3.16}$$

The cost of producing electricity of the conventional generator is calculated using piecewise linear cost function equations as demonstrated in the next section (3.18) – (3.21).

3.2.3 Piecewise Linearization of Thermal Production Cost Model

Quadratic production cost function of thermal units is typically expressed [50] as follows:

$$E_g(P_{tg}^{ac}) = FC_g(a + bP_{tg}^{ac} + c(P_{tg}^{ac})^2) \tag{3.17}$$

As well known, the quadratic cost of production (3.17) is not linear. As proposed in [54] and [55], the quadratic cost of production of thermal units (3.17) can be linearized as follows:

$$E_g(P_{tg}^{ac}) = FC_g(u_{tg} \cdot AA_g + \sum_{e=1}^{N_g} F_{eg} \cdot \delta_{etg}) \tag{3.18}$$

$$0 \le \delta_{etg} \le \tau_{eg} - \tau_{eg-1} \tag{3.19}$$

$$P_{tg}^{ac} = \underline{P_g} \cdot u_g + \sum_{e=1}^{N_e} \delta_{etg} \tag{3.20}$$

$$AA_g = A_g + b_g \underline{P_{tg}^{ac}} + c_g \underline{P_{tg}^{ac^2}} \tag{3.21}$$

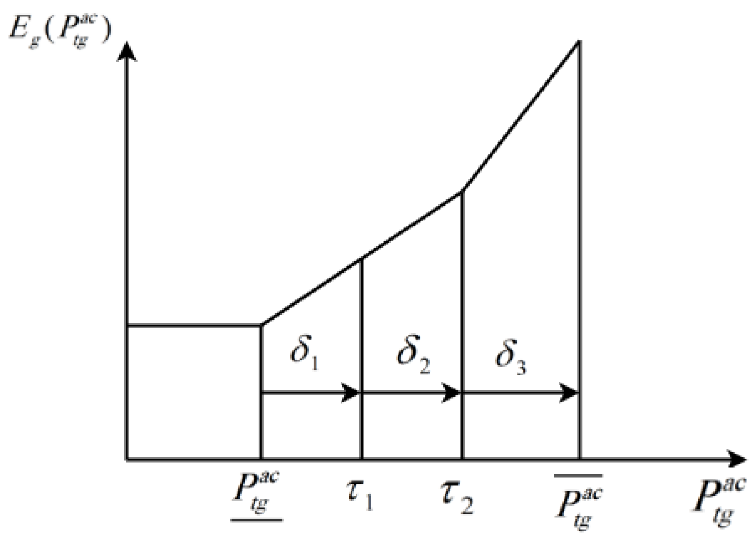

Figure 3.2: Piecewise linear production cost.

As shown in Figure 3.2, the cost function in (3.17) can be accurately approximated by a set of piecewise linear cost functions (3.18 – 3.21). The parameters FC_g, u_{tg}, AA_g and F_{eg} in equation (3.18) are the thermal fuel cost, the initial state, coefficient cost and slope segment of the piecewise linear production, respectively. The only decision variable in equation (3.18) is the thermal power output segment of a piecewise linear thermal heat rate curve (δ_{etg}).

Equation (3.19) shows the constraint of δ_{etg} with considering break point of a segment of the piecewise linear (τ_{eg}) for the maximum limit. The summation of variable δ_{etg} must equal the output of the thermal generator (P_{tg}^{ac}) as stated in equation (3.20). Notice that the number of thermal power output segment (δ_{etg}) depends on the break point of the segment of the piecewise linear (τ_{eg}).

The cost coefficient (AA_g) is described in equation (3.21). A_g, B_g, C_g shown in equation (3.21) are cost coefficients of quadratic thermal cost function. As a result, the equations (3.18 – 3.21) are linearized, so the nonlinear cost function in (3.17) can be accurately approximated using piecewise linear cost functions.

The decision variables of the proposed model for the optimal operation are summarized in the Table 3.2.

Table 3.2: Optimal peration variables and functions

Variable	Function
DF	Daily profits
BID_{dt}	Buying/selling energy from/to market
SOC_{dt}	State of charge of ESS
ESS_{dt}	Power output of ESS
GG_{dt}	Depreciation cost of ESS
P_{dt}^{TG}	Power output of TG
E_{dt}	Operation cost of TG

3.3 Case Study

In this subsection, the optimization model of ADN (3.1) – (3.16) are solved with considering piecewise linearization of thermal production cost model presented in section 3.2.3 to maximize the DSO's total profits. The most important set of planning problem is to find the optimal sizing of DERs.

3.3.1 Description of Case Study

The case study examines the investment option in the ADN and how to determine optimum sizing of ADN’s resources in order to maximize profits to DSO.

The planning horizon for the project is eight years. It is assumed in this case study the load will be double at the end of planning period. The year is represented by representative days that are weighted by a scaling factor. It has been taken two samples; one sample represents summer, and one sample represents winter each sample represents 6 months "180 days" and each sample consists of 24 hours as approached in [48].

The proposed ADN model has been tested on the electricity market in Texas, Electric Reliability Council of Texas (ERCOT) [60]. The load profiles, MCP and actual wind outputs are obtained from [60]. However, data of solar output in Texas are not available, so prediction of solar output in Texas is made by National Renewable Energy Laboratory (NREL) [61]. The solar panel specifications used in NREL to predict the production of solar in Texas are summarized in the Table 3.3.

Table 3.3: The specifications of PV system

PV system size	**1 MW**
Module type	Premium
Array type	2- Axis tracking
System losses	14.08 %

The MCP and load profile for two representative days at ERCOT are shown in Figure 3.3 and Figure 3.4 ,respectively.

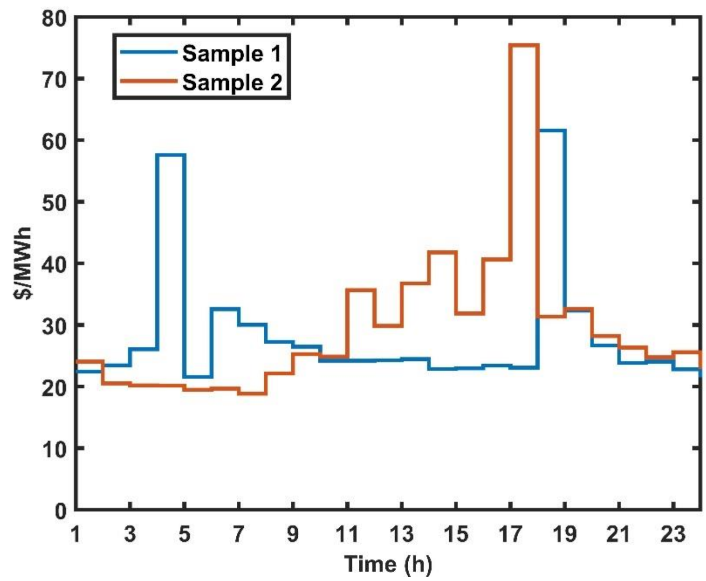

Figure 3.3: Energy prices at ERCOT for the two representive days.

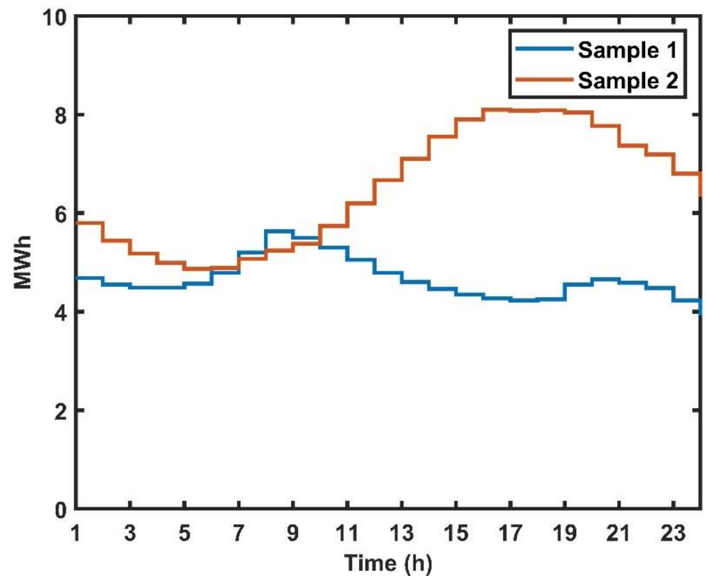

Figure 3.4: Load profile at ERCOT for the two representive days.

However, the PV and WT profiles are normalized as shown in Figure 3.5 and Figure 3.6, respectively. Hence, the production of PV and WT are equal to the optimal capacity "based on the optimization results" multiplied by the normalized profile of each resource.

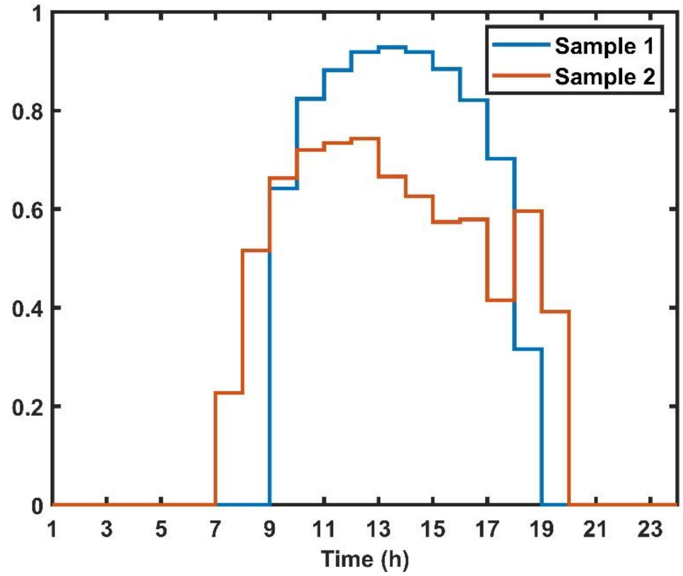

Figure 3.5: Normalized PV power output for the two representive days.

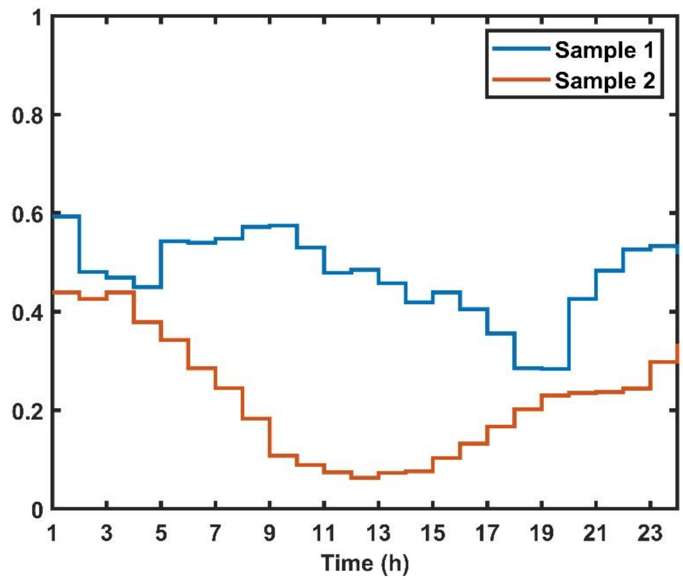

Figure 3.6: Normalized WT power output for the two representive days.

The capital cost and maintenance cost of the renewable resources and ESS are adapted from [62], and the capital cost and maintenance cost of thermal generator is taken from [63]. The technical and economic parameters of RESs and ESS are provided in Table 3.4.

Table 3.4: The costs and lifespan of DERs

Type of Resource	Capital Cost	Annual O&M Cost	Lifespan
TG	318 $/kw	61.32 $/kw	20
PV	1343 $/kw	12 $/kw	25
WT	950 $/kw	27 $/kw	25
ESS	175 $/kw	2 $/MWh	10
	225 $/kwh	4.00 $/kw	

The cost coefficients (A, B and C) of the conventional generation units are $0.09\$/h(MW)^2, 10\$/h(MW)$ and $120\$$ respectively as adapted from [64].

3.3.2 Results

The performance of the proposed ADN model is assessed where the DSO has different alternatives, i.e. purchase/ selling electricity from/to the wholesale market, installing DERs, that makes the highest profits to DSO and meet the load requirement.

The total payoff and the optimal sizing od DERs at the end of the project is shown in Figure 3.7. It is clear from Figure 3.7, the SV is very low compared to TI because the investment in DERs are made in the beginning of planning horizon. As well known, the SV depends on the lifetime of assets. Since the lifespan of ESS is very low, so it is expected that the SV will be decreased in this case study.

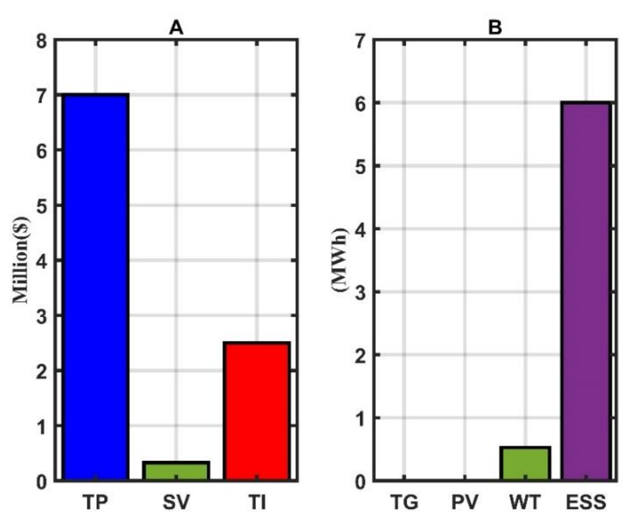

Figure 3.7: Without network constraints (A) Optimal payoff, (B) Optimal sizing of DERs

As demonstrated in Figure 3.7, the optimal results show that there is no interest to install TG and PV and there is very low installed capacity of WT. However, ESS is the most profitable resource among other resources. The selected ESS is expected because of the high investment costs of RESs and the high operating costs of TG.

In addition to that since the network constraint is not taken into account, the ESS can charge/discharge during off-peak/peak demand at low/high MCP to maximize the profits to DSO easily without considering voltage and capacity of lines limits.

CHAPTER 4

DSO PLANNING WITH NETWORK MODEL

4.1 Distribution Network Model

The power flow constraints of the distribution network in this paper are based on the work presented in [53]. This is based on the three-phase power equations specified by:

$$P_i = \sum_{j=1}^{n} G_{ij} V_i V_j cos\theta_{ij} + \sum_{j=1}^{n} B_{ij} V_i V_j sin\theta_{ij} \tag{4.1}$$

$$Q_i = -\sum_{j=1}^{n} B_{ij} V_i V_j cos\theta_{ij} + \sum_{j=1}^{n} G_{ij} V_i V_j sin\theta_{ij} \tag{4.2}$$

The following assumptions were made to linearize these nonlinear relations:

1. The absolute value of phase angle differences across lines are within 10 degree.
2. The shunt conductor is neglected.
3. As the voltages are all close to 1 under normal conditions, the voltage multiplication is linearized as presented in [53] as follows:

$$V_i (V_i - V_j cos\theta_{ij}) \approx (V_i - V_j) \tag{4.3}$$

Moreover, the admittance matrix of the power system is the sum of the non-diagonal elements in the corresponding rows, with the contribution of shunt elements as well:

$$Y_{ij} = \begin{cases} -y_{ij} & if \quad j = i \\ y_{ii} + \sum\limits_{k=1, k \neq i}^{n} y_{ik} & if \quad j = i \end{cases} \tag{4.4}$$

The admittance matrix consists of conductance and susceptance as shown in equation (4.5):

$$Y_{ij} = G_{ij} + jB_{ij} \tag{4.5}$$

With those assumptions in mind, real power equation (4.1) can be decoupled to the voltage magnitudes and the phase angles.

$$= g_{ii}V_i^{\,2} + \sum_{j=1, j\neq i}^{n} (g_{ij}V_i(V_j - V_j \operatorname{Cos}\theta_{ij}) - b_{ij}V_iV_j \operatorname{Sin}\theta_{ij}) \tag{4.6}$$

With considering the phase angles (θ_{ij}) are within 10 degree, $\operatorname{Cos}\theta_{ij}$ equals 1 and $\operatorname{Sin}\theta_{ij}$ equals $(\theta_i - \theta_j)$ based on small-angle approximation Moreover, the voltage magnitude (V_i) assumed to be 1, so equation (4.6) can be approximated as shown in equation (4.7).

$$\approx g_{ii}V_i + \sum_{j=1, j\neq i}^{n} g_{ij}(V_i - V_j) - \sum_{j=1, j\neq i}^{n} b_{ij}(\theta_i - \theta_j) \tag{4.7}$$

After that, some arrangements applied on equation (4.7) to get equation (4.8).

$$= \left(V_i \sum_{j=1}^{n} g_{ij} + \sum_{j=1, j\neq i}^{n} (-g_{ij})V_j\right) - \left(\theta_i \sum_{j=1, j\neq i}^{n} b_{ij} + \sum_{j=1, j\neq i}^{n} (-b_{ij})\theta_j\right) \tag{4.8}$$

With considering equations (4.4) and (4.5), the equation (4.8) can be combined as shown in equation (4.9)

$$P_i = \sum_{j=1}^{n} G_{ij}V_j - \sum_{j=1}^{n} B'_{ij}\theta_j \tag{4.9}$$

Similarly, equation (4.2) for reactive power can be approximated as follows:

$$Q_i = -\sum_{j=1}^{n} B_{ij}V_j - \sum_{j=1}^{n} G_{ij}\theta_j \tag{4.10}$$

The form of the matrix of equations (4.9) and (4.10) as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = -\begin{bmatrix} B^{'} & -G \\ G & B \end{bmatrix} \begin{bmatrix} \theta \\ V \end{bmatrix} \tag{4.11}$$

4.2 Network Expansion Planning Model

Both the addition of new lines and the extension of existing lines are included in this study. The addition of new lines to the existing network is considered as follows:

$$f_{ij} \le B_l X_l^{NL} (\Theta_i - \Theta_j) \tag{4.12}$$

$$-f^{max} \le f_{ij} \le f^{max} \tag{4.13}$$

Note that in (4.12), the binary variable X_l^{NL} is used to decide whether to add new line or not. However, the equation (4.12) is not linear as X_l^{NL} and $(\Theta_i - \Theta_j)$ are variables. The linearization of adding new lines considered in this paper is based on the work presented in [56]. The addition of new lines can be linearized as follows:

$$-(1 - X_l^{NL}) \cdot Z \le \frac{f_{ij}}{B_l} - (\Theta_i - \Theta_j) \le (1 - X_l^{NL}) \cdot Z \tag{4.14}$$

$$-X_l^{NL} \cdot f_l^{max} \le f_{ij} \le X_l^{NL} \cdot f_l^{max} \tag{4.15}$$

Z is a parameter which should be equal to a large positive constant number. If X_l^{NL} is equal to zero, equation (4.14) will be vanished, and equation (4.15) will be inactive. On the other hand, if X_l^{NL} equals to one, equation (4.14) must be equal to $B_l (\Theta_i - \Theta_j)$, while the limited capacity of the new line will be equal to equation (4.15).

The following strategy is used to determine the most candidate lines to be upgraded:

1. Assuming that the load is doubled before the problem is resolved.
2. A partial of the optimization problems was run with all candidate lines that are overloaded.
3. The lines that selected to be upgraded are considered as candidate lines to be considered in whole optimization problem.

Figure 4.1 shows the summarized strategy to select the candidate lines to be upgraded.

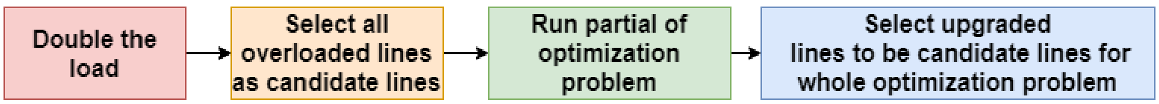

Figure 4.1: Candidate lines approach

The main purpose of using this strategy is minimize the number of candidate lines to be upgraded it order to reduce the number of candidate lines to be upgraded, so the size of the problem will be reduced.

4.3 Problem Formulation

In this section, the linearized distribution network model and network expansion planning model are added to the previous model. The purpose of that is to address the network constrains such as voltage/angle limits and the line capacity as well as enhancing existing network including adding/upgrading new/existing lines to the existing network. Thus, the model is not only required to find the optimal capacity of DERs, but it is also required to find the optimal location of DERs and optimal selective lines to be added/upgraded. Thus, the optimal location and sizing of DERs and network expansion planning are addressed in planning aspect and network constrains are addressed in the operation aspect.

4.3.1 Planning Optimization Model

The optimal solution needs to find not only optimal DERs sizing, but also the optimal DERs location with integrating the linearized distribution network model with proposed model. Thus, the investment cost of TG, PV, and WT are modified from (3.4) to (4.16), (3.5) to (4.17), and from (3.6) to (4.18), respectively. In addition, the investment cost of ESS in equation (3.7) is modified to (4.19). The summations are added to all equations (4.16), (4.17), (4.18) and (4.19) to find the total installed capacity in all buses of TG, PV, WT, and ESS, respectively.

$$C_{INV}^{TG} = \sum_{k=1}^{K} N_k^{TG} C_{CAP}^{TG} \tag{4.16}$$

$$C_{INV}^{PV} = \sum_{k=1}^{K} N_k^{PV} C_{CAP}^{PV} \tag{4.17}$$

$$C_{INV}^{WT} = \sum_{k=1}^{K} N_k^{WT} C_{CAP}^{WT} \tag{4.18}$$

Where N_k^{TG}, N_k^{PV} and N_k^{WT} are the decision variables used to find the optimal location and capacity of TG, PV, and WT in bus k, respectively.

Equation (4.19) is used to calculate the investment cost of ESS. MP_k and ME_k are decision variables are used to determine the optimal sizing and location power rating and energy capacity of ESS at each bus.

$$C_{INV}^{ESS} = \sum_{k=1}^{K} (C_{CAP}^{P} \cdot MP_k + C_{CAP}^{E} \cdot ME_k) \tag{4.19}$$

Two new equations are added to add/upgrade lines. Equations (4.20) and (4.21) are used to calculate the cost of adding new lines and upgrading the existing lines, respectively. Note that the model NEP to add new lines is calculated using the linearized equations (4.14-4.15) as demonstrated in the Sec. 4.2.

$$C_{INV}^{NL} = \sum_{l=1}^{NL} X_l^{NL} C_{CAP}^{NL} LL_l \tag{4.20}$$

$$C_{INV}^{UL} = \sum_{l=1}^{NL} X_l^{UL} C_{CAP}^{UL} LL_l \tag{4.21}$$

Salvage value (SV) is also modified from (3.8) to (4.22).

$$SV = \sum_{n=1}^{Type} \sum_{k=1}^{K} N_k^n C_{INV}^n \frac{Y_{rem}^n}{Y_{com}^n} \tag{4.22}$$

Where $N^n C_{INV}^n$ are used to calculate the investment cost of each type of resource at each bus k.

The decision variables of the proposed model are modified according to network constraints and NEP for the planning optimization in Table 4.1.

Table 4.1: Planning decision varirables with network model.

Variable	Function
N_k^g, N_k^{PV}, N_k^{WT}	Sizing of TG, PV and WT in each bus, respectively
ME_k, MP_k	Capacity sizing and power rating of ESS in each bus, respectively
X_l^{NL}	Binary to add new lines
X_l^{UL}	Binary to upgrade existing lines

4.3.2 Operation Optimization Model

To integrate the linearized distribution network model with proposed model, balance equation is modified from (3.10) to (4.25). The balance equation in (4.25) captures the production of DERs and demand in each bus as well as the BID_{dt}.

$$\sum_{k=1}^{K} (N_k^s P_{dt}^s + N_k^w P_{dt}^w + P_{dtk}^g) = BID_{dt} + \sum_{k=1}^{K} (L_{dtk} + ESS_{dtk}) \tag{4.23}$$

Inequalities (3.13), (3.14) and (3.15) shall be modified to (4.24), (4.25) and (4.26), respectively. Thus, the modified equations specify the maximum power rating, energy capacity limits and state of charge of ESS in each bus as shown in (4.24), (4.25) and (4.26), respectively.

$$\underline{MP_k} \le ESS_{dtk} \le \overline{MP_k} \tag{4.24}$$

$$\xi \underline{ME}_k \le SOC_{dtk} \le \xi \overline{ME}_k \tag{4.25}$$

$$SOC_{dtk} = SOC(d,t-1,k) + ESS_{dtk} \tag{4.26}$$

The minimum/ maximum limit of TG at each bus is also modified from (3.16) to (4.27).

$$\underline{P_{dtk}^{TG}} \le P_{dtk}^{TG} \le \overline{P_{dtk}^{TG}} \tag{4.27}$$

The limit of the minimum and maximum of voltage magnitude and angle are set out in (4.28) and (4.29), respectively.

$$\underline{V_k} \le V_{dtk} \le \overline{V_k} \tag{4.28}$$

$$\underline{\theta_k} \le \theta_{dtk} \le \overline{\theta_k} \tag{4.29}$$

The operation decision variables of the proposed model for the optimal operation are modified as shown in Table 4.2.

Table 4.2: Operation decision varirables with network model.

Variable	Function
BID_{dt}	Buying/selling energy from/to market
ESS_{dtk}	Power output of ESS
SOC_{dtk}	State of charge of ESS
P_{dtk}^{TG}	Power output of TG
V_{dtk} , θ_{dtk}	Voltage magnitude and phase angle, respectively.

4.4 Case Study

In this subsection, the problem is firstly solved without NEP. Then, the same parameters will be used to solve the problem with NEP. The purpose of that is study the effect of NEP in the proposed model. In this case study, the optimization model of ADN (4.18) – (4.31) including the equations presented in Sec. 3.21, Sec. 3.22 and Sec. 3.33 is solved to maximize the DSO's total profits. The most important set of planning problem is to find the optimal sizing and location of DERs as well as optimal lines to be added and upgraded.

4.4.1 Description of Case Study I Without NEP

The case study examines the investment option in the ADN and how to determine optimum sizing and setting of ADN's resources in order to maximize profits to DSO. The proposed ADN model is implemented to a medium voltage 38 radial distribution test system [59] as shown in Figure 4.2. The capacity of the feeder in this network is 5 MVA.

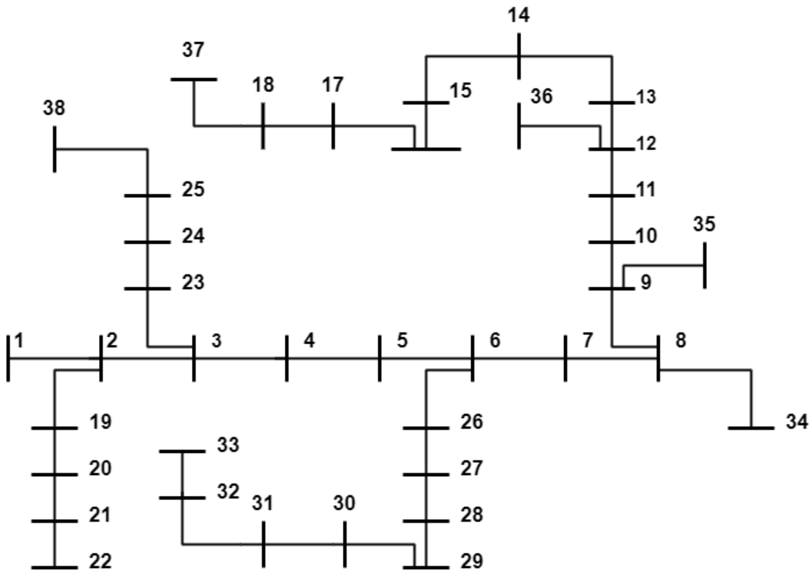

Figure 4.2: Radial Distribution network.

The planning horizon for the project is assumed to be eight years. It is assumed in this case study the load will be double at the end of project horizon.

The same data for PV, WT and load that presented in section 3.3 are used in this case. However, Texas load profile is normalized as shown in Figure 4.3. After that, the load profile is distributed across the test system by multiplying the normalized load profile with the existing fixed load as in 38 bus radial distribution test system to get the load profile in each bus.

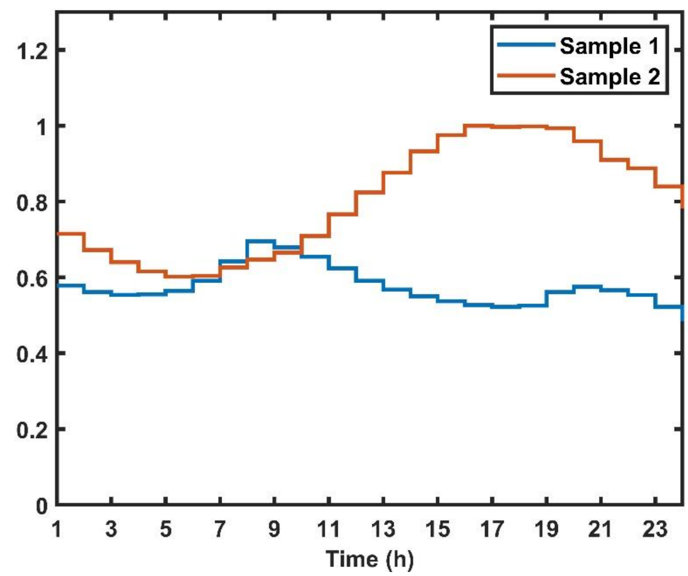

Figure 4.3: Normalized load profile for the two representive days

In this case study, a set of preliminaries and assumptions shall be made as follows:

- All busses are candidates for DERs placement and experience uniform wind speed and solar radiation.
- The upper and lower bus voltages need to be maintained within 1.05 and 0.95, respectively.
- Discount rate considered in this work is 7%.

The capital cost and maintenance cost of DERs as well as the cost coefficients (A, B and C) of TG units are the same data used in case study presented in section 3.3.

4.4.2 Results of Case Study I without NEP

This section is devoted to the application of the proposed model to find the optimal location and sizing of DERs to maximize the total payoff to DSO. It is also considered the network constraint.

The total payoff and optimal sizing of DERs at the end of the project horizon is shown in Figure 4.4. It is clear from Figure 4.4, the RESs are more profitable than ESS and TG. In this case study, assumed that the investment shall be made at the beginning of the planning period and serve for eight years, so the salvage value (SV) of RESs are higher than ESS because the lifespan of RESs are more than ESS. In addition, there is no operating costs of RESs compared to TG, so it is obvious the RESs are more attractive. Even if the operating costs are considered, the operating cost of RESs are much less the operating costs of TG.

The ESS in this case study is less attractive compared to the case study presented in Sec. 3.32 because the network constraints are taken into account. In case study presented in Sec. 3.3.2, single bus is considered, so ESS can be used to interact with the grid directly to charge/discharge during off-peak/peak demand at low/high MCP to serve the local load and to maximize the total payoff to DSO. However, in this case study, the load is distributed over the 38 bus and the voltage/angle limits are considered, so ESS cannot distribute all energy from one bus to all loads across the buses.

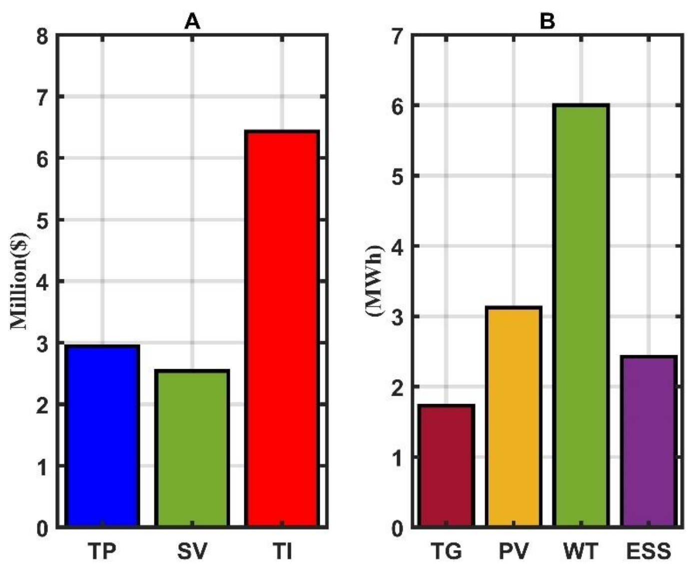

Figure 4.4: Without NEP (A) Optimal payoff, (B) Optimal sizing of DERs.

The distribution of DERs across the network is demonstrated in Table 4.3. As shown in Table 4.3, the capacity installation of RESs in each bus does not exceed 1 MWh. To elaborate the reason, the RESs are not controllable and weather-dependent, so they may produce more than expected causing voltage/angles challenges to the DSO. Installing less capacity of RESs helps to maintain the network constraints even they produced more than expected.

Table 4.3: The distribution of DERs

PV (MWh)		WT (MWh)	
Bus 7	0.595	Bus 8	0.821
Bus 8	0.2	Bus 9	0.867
Bus 9	0.2	Bus 11	0.312
Bus 12	0.546	Bus 12	0.699
Bus 13	0.2	Bus 13	0.394
Bus 17	0.307	Bus 15	0.216
Bus 19	0.277	Bus 16	0.2
Bus 20	0.23	Bus 17	0.2
Bus 22	0.28	Bus 19	0.657
Bus 37	0.289	Bus 20	0.2
Bus 7	0.595	Bus 22	0.2
TG (MWh)		Bus 21	0.474
Bus 37	1.873	Bus 33	0.2
-	-	Bus 37	0.559
ESS (MW)		**ESS (MWh)**	
Bus 12	0.256	Bus 12	0.444
Bus 14	0.236	Bus 14	0.43
Bus 17	0.2	Bus 17	0.394
Bus 20	0.2	Bus 20	0.45
Bus 22	0.2	Bus 22	0.43
Bus 37	0.2	Bus 37	0.28

4.4.3 Description of Case Study II With NEP

In this case study, the same model and parameters used in **Case Study I** will be used in this case study. However, in this case study, the network expansion planning (NEP) will be considered to study how enhancing the network effect the results.

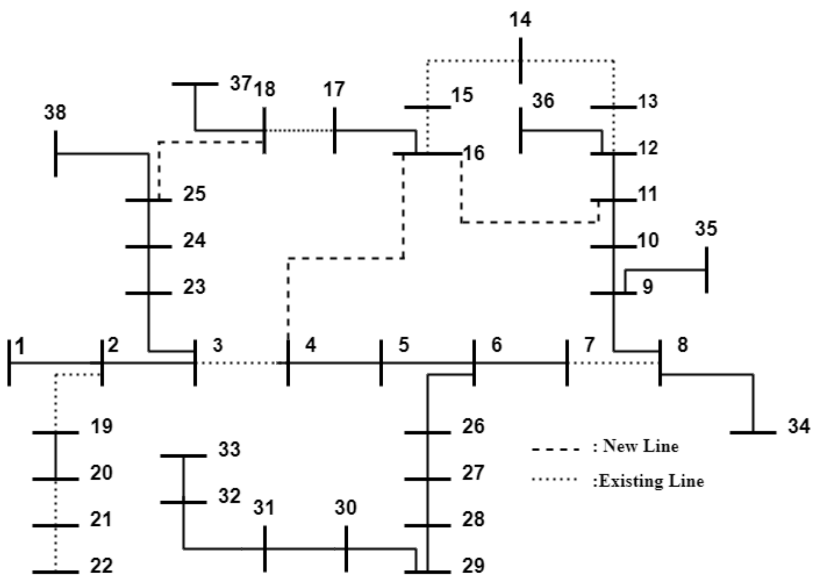

Figure 4.5: Radial distribution network with NEP

In this case study, the same set of preliminaries and assumptions used in the previous case study shall be used in this case study. However, there are two assumptions for enhancing the network as listed below:

- The candidate buses for DERs placement are selected based on the approach set out in section 4.2, so the candidate buses for DGs are shown on Figure 4.5.
- The candidate construction of new line between two buses are selected arbitrary as shown in Figure 4.5.

The capital cost of adding/upgrading lines is 86100 $/MVA and adapted from [52].

4.4.4 Results of Case Study II With NEP

The performance of the proposed ADN model is assessed where the DSO operator has different alternatives, i.e. purchase/selling electricity from/to the wholesale market, installation of DERs units and/or enhancing the existing network.

The optimal profits and optimal sizing of DERs at the end of the project horizon is demonstrated in Figure 4.6. As shown in Figure 4.6, the optimal payoff is increased by 50% from $4.41 million to $2.94 million compared to the previous case study presented in Sec. 4.42 without considering NEP.

In addition, taking into account NEP, the installed capacity of ESS is increased by 59% from 2.428 MWh in case presented in Sec. 4.42 to 3.883 MWh. However, there is no interest to install TG in this case study. To elaborate the reason, ESS is charged from DGs or the grid from various buses, so NEP makes the network more reliable for ESS to be charged form different buses. Furthermore, since TG generates the required energy to sustain the load, there is no need to move energy from other buses such as ESS, so enhancing the network is not required to make TG more appealing.

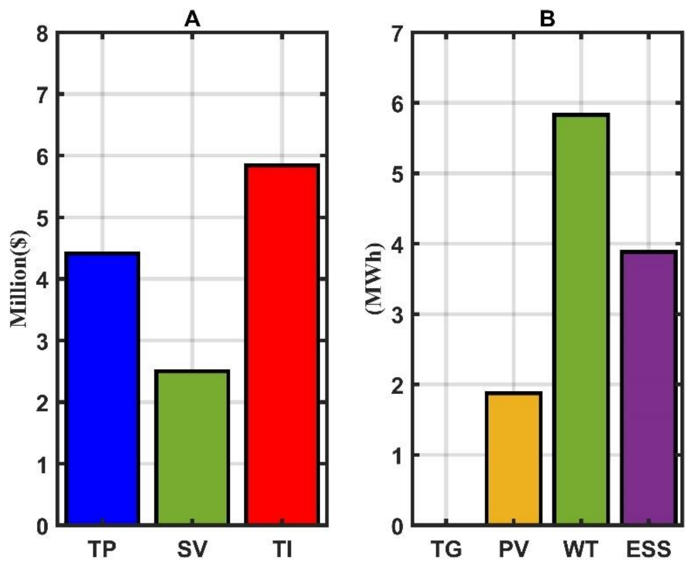

Figure 4.6: With NEP (A) Optimal payoff, (B) Optimal sizing of DERs.

The optimal location and sizing of RESs in each bus is shown in Table 4.4. In the case study presented in Sec. 4.4.2, the installed capacity of RESs in each bus has not been more than 1 MWh to maintain the network constrains as RESs are not controllable. In this case study, taking into account NEP, there is only one bus installed 1.767 MWh capacity of WT in bus 12, which is more than 1 MWh. In addition, the highest capacity of PV is installed in bus 12 which is 0.958 MWh. To elaborate the reason, bus 12 is connected to three buses which are 11-12, 12-13, and 12-36, so the loads in these three buses consumed all the production of RESs. In addition to that there is an installed capacity of ESS in bus 12, even the RESs produce more than expected, the excess of energy will be stored in ESS to maintain the network constraints.

Table 4.4: Distribution of DERs at each bus considering NEP

PV (MWh)		WT(MWh)	
Bus 12	0.958	Bus 9	0.769
Bus 13	0.2	Bus 11	0.468
Bus 15	0.345	Bus 12	1.767
Bus 17	0.373	Bus 15	0.486
-	-	Bus 17	0.652
-	-	Bus 20	0.639
-	-	Bus 21	0.2
-	-	Bus 22	0.448
-	-	Bus 33	0.2
-	-	Bus 37	0.2
ESS (MW)		ESS (MWh)	
Bus 12	0.206	Bus 12	0.635
Bus 13	0.2	Bus 13	1.432
Bus 15	0.2	Bus 15	0.225
Bus 17	0.2	Bus 17	0.841
Bus 22	0.2	Bus 22	0.75

In the case study, there are three candidate lines to be added and ten candidate lines to be upgraded. However, one line is added and five lines are upgraded as shown in Table 4.5. Thus, taking into account NEP, RESs and ESS are the selected resources to maximize the overall payoff to DSO, to meet the local load requirements and to avoid the operating cost of TG.

Table 4.5: Selected lines

Selected new Line	
Line 4-16	
Selected Upgrading Line	
Line 2-19	Line 21-22
Line 3-4	Line 17-18
Line 14-15	-

CHAPTER 5

DYNAMIC PLANNING MODEL WITH TWO STAGE STOCHASTIC PROGRAMMING

5.1 Dynamic Planning Model

The dynamic planning model approached in this research work is according to pseudo-dynamic strategy [40]. Pseudodynamic methodology involves two stages. In the first stage, a static planning model is solved in order to achieve a solution that can optimally satisfy the demand needs for the final year of the planning period. In the second stage, the effect of load growth is explicitly taken into account and the optimal solution of DG placement and network expansion is continuously concatenated in a single stage. An optimal intermediate solution is obtained for each intermediate year between the first and the final year of the planning period. Each intermediate solution considers only the buses to locate DGs which have been obtained from the first stage onwards. The comprehensive steps of the proposed dynamic planning model, taking into account the pseudo-dynamic approach, are as follows:

1. Determine the forecasted demand across the network buses for last year of the planning period.
2. Solve the problem for final year taking into account all buses as a possible option for DERs placement to specify the candidate buses to be considered in next steps.
3. Solve the problem considering the load growth in the first year of the planning period with considering candidate buses that have been identified in Step 2. The achieved result is the optimal solution for this year. For the following year, all DERs selected for installation and lines to be added/upgraded in this year will be considered as existing.

4. Specify the load growth in the next intermediate year, go to step 3. If the problem has been solved for all intermediate years of the planning period, stop.

Figure 4.1 shows the summarize of dynamic planning approached considered in this research work.

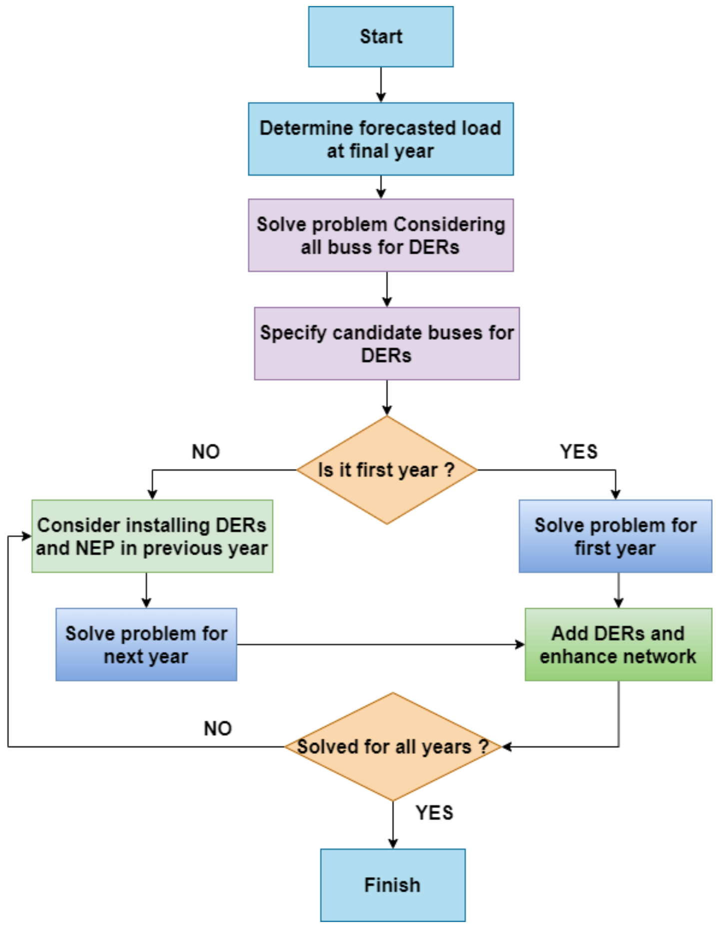

Figure 5.1: Dynamic Planning Approach.

The candidate upgrading lines are selected based on the approached presented on Sec. 4.2. However, the candidate lines to be added are selected arbitrary. Besides, the candidate lines to be upgraded or added to the existing network shall be considered in each intermediate year.

5.2 Ancillary Services Model

The DSO participates in the day-ahead ancillary services (AS) market and energy market as shown in Figure 5.2. The DSO provides regulation up, regulation down, and reserve capacity.

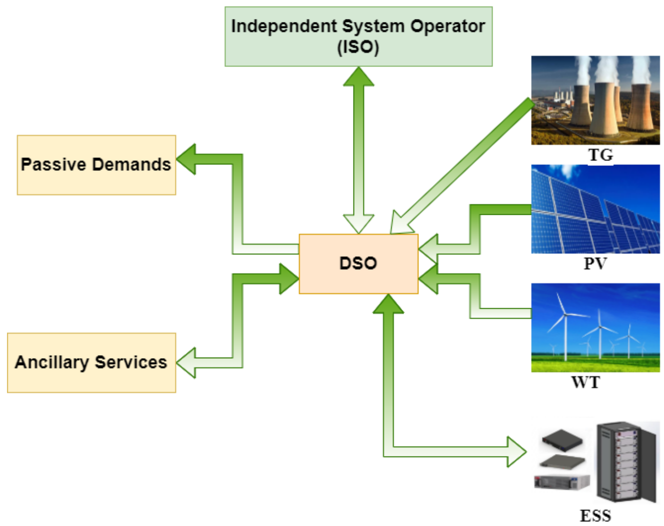

Figure 5.2: System model with AS

In the day-ahead AS market, the ISO conducts AS plans and provides AS information that identifies required capacities and prices on an hourly basis. Following that, each participant should submit bids for providing AS to ISO, including hourly capacity. After that, the ISO performs its own optimization. Finally, the ISO posts the accepted bids. In real time, ISO sends signal requesting the percentage from the total bided capacity from accepted bids to provide the service required such as regulation up/down and/or reserve capacity.

5.3 Problem Formulation

In section 3.2, the model is addressed to find the optimal sizing of DERs. Then, in section 4.1, the network model constraint is incorporated with the proposed model. Following that, the NEP is also described in section 4.2. In this section, the complete model will be addressed and explained to make easy for the reader to know and understand the complete model. Moreover, the dynamic planning (DP) and ancillary services (AS) will be incorporated with the proposed model.

Note that, the equations that are explained and described in section 3.2 and section 4.3, it will not be explained here once again. The only new variables and equations will be explained and described. For more explanation and details, the reader can refer to section 3.2 and 4.3.

5.3.1 Planning Optimization Model

The objective function of this research is described in (5.1). Maximize:

$$\text{TF}=\text{AP} + \text{SV} - \text{TI} \tag{5.1}$$

Equation (5.2) calculate the profits on an annual basis, taking into account the discount rate and the maintenance cost of DERs. In addition, the sizing of DERs namely, TG (N_y^{TG}), PV (N_y^{PV}), WT (N_y^{WT}), and ESS (MP_y, ME_y) change in annual basis, so the maintenance cost of each resource is also changed and depends on the sizing.

$$AP = \sum_{y=1}^{NY} (1+r)^{-y} (DP - N_y^{TG} C_{min}^{TG} - N_y^{PV} C_{min}^{PV} - N_y^{WT} C_{min}^{WT} - ME_y \cdot C_{min}^{E} - MP_y \cdot C_{min}^{P}) \tag{5.2}$$

The total investment costs (TI) of DERs and enhancing the existing network are calculated in (5.3).

$$TI = (C^s + C^w + C^{ESS} + C^g + C^{NL} + C^{UL})_{INV} \tag{5.3}$$

Equations (5.4) and (5.5) are used to calculate the cost of adding new lines and upgrading the existing lines, respectively. Moreover, these two variables (X_{yl}^{NL}, X_{yl}^{UL}) do not capture only the added/upgraded lines, but also capture in which year these lines are added/upgraded.

$$C_{INV}^{NL} = \sum_{y=1}^{NY} \sum_{l=1}^{N} X_{yl}^{NL} C_{CAP}^{NL} LL_l \tag{5.4}$$

$$C_{INV}^{UL} = \sum_{y=1}^{NY} \sum_{l=1}^{N} X_{yl}^{UL} C_{CAP}^{UL} LL_l \tag{5.5}$$

Equations (5.6), (5.7) and (5.8) are used to determine the investment cost in annual basis of TG, PV and WT, respectively. N_{yk}^{TG}, N_{yk}^{PV} and N_{yk}^{WT} are used to determine the optimal sizing and location of TG, PV and WT, respectively. Moreover, there three variables determine the size of DERs in annual basis.

$$C_{INV}^{TG} = \sum_{y=1}^{NY} \sum_{k=1}^{K} N_{yk}^{TG} C_{CAP}^{TG} \tag{5.6}$$

$$C_{INV}^{PV} = \sum_{y=1}^{NY} \sum_{m=k}^{K} N_{yk}^{PV} C_{CAP}^{PV} \tag{5.7}$$

$$C_{INV}^{WT} = \sum_{y=1}^{NY} \sum_{k=1}^{K} N_{yk}^{WT} C_{CAP}^{WT} \tag{5.8}$$

Equation (5.9) is used to calculate the investment cost of ESS. MP_{yk} and ME_{yk} are decision variables are used to find the optimal sizing and location power rating and energy capacity of ESS at each bus (k) on annual basis.

$$C_{INV}^{ESS} = \sum_{y}^{NY} \sum_{k=1}^{K} C_{CAP}^{P} \cdot MP_{yk} + C_{CAP}^{E} \cdot ME_{yk} \tag{5.9}$$

Salvage value is used for properties with longer lifespans than the planning period. Equation (5.10) helps the DSO to calculate the salvage value of the assets with considering the installation time of the assets. In the previous chapters, all the DERs are installed in the beginning of planning horizon, so the salvage value of all DERs is calculated based on the lifespan of assets and the planning horizon. However, in this chapter, = the salvage value of resource will be changed depending on installation year, the lifespan of the resource and the planning horizon.

$$SV = \sum_{n=1}^{Type} \sum_{y=1}^{NY} \sum_{k=1}^{K} N_{yk}^{n} C_{INV}^{n} \frac{Y_{rem}^{n}}{Y_{com}^{n}} \tag{5.10}$$

Where $N_{yk}^{n}C_{INV}^{n}$ are used to calculate the investment cost of each type of resource annually and Y_{com}^{n} and Y_{rem}^{n} are the lifetime of the component in years and the remaining lifetime of the component in years, respectively.

The planning decision variables in the complete model are summarized in Table 5.1.

Table 5.1: Planning decision varisbles in complete model

Variable	Function
TF	Total profits ($)
AP	Annual profits ($)
TI	Total investment ($)
SV	Salvage value ($)
$C_{INV}^{NL}, C_{INV}^{UL}$	Investment cost of adding and upgrading lines, respectively.
$C_{INV}^{TG}, C_{INV}^{PV}, C_{INV}^{WT}$	Investment cost of TG, PV and WT, respectively
C_{INV}^{ESS}	Investment cost of ESS
N_{yk}^{TG}, N_{yk}^{PV}, N_{yk}^{WT}	Sizing of TG, PV and WT in each bus, respectively
ME_{yk}, MP_{yk}	Capacity sizing and power rating of ESS in each bus, respectively
X_{yl}^{NL}	Binary to add new lines
X_{yl}^{UL}	Binary to upgrade existing lines

5.3.2 Operation Optimization Model

The expected daily profits (DP) for DSO is given in (5.11). The first term is the BID, buy/sell energy at MCP from wholesale market. The second term is the income from selling energy to consumers. The third, fourth and fifth terms are used to calculate the income from participating in AS market to provide reserve capacity, regulation up and regulation down, respectively. The sixth and seventh terms are used to calculate the operation cost of TG and the depreciation cost of ESS, respectively.

$$DP = \sum_{y}^{NY}\sum_{d=1}^{D}\sum_{t=1}^{T} K_d \cdot ((\pi^{ISO} BID)_{ydt} + \sum_{k=1}^{K}((\pi^{L} L + \pi^{R} R^{R} + \pi^{U} R^{U} + \pi^{D} R^{D} - E - GG)_{ydtk})) \quad (5.11)$$

Equation (5.12) ensures the balance between the total generation and demand at each hour. In addition, the AS signals are considered in balance equation (5.12). R^U, R^D and R^R are regulation up, regulation down and reserve capacity, respectively. the R^D is positive as seen in (5.12), it means that ESS is charged to provide regulation down. However, R^U and R^R are negative, so ESS is discharged to provide regulation up and reserve capacity.

$$\sum_{k=1}^{K}(N_{yk}^{s} P_{dt}^{s} + N_{yk}^{w} P_{dt}^{w} + P_{ydtk}^{g}) = BID_{ydt} + \sum_{k=1}^{K}(L + ESS + R^{D} - R^{U} - R^{R})_{ydtk} \quad (5.12)$$

Equation (22) shows that the ESS depreciation cost GG is positive only when the ESS is discharged as discussed in [58]73. Otherwise, it's zero. Using ESS as charging/discharging frequently reduces the lifetime of ESS due to the increased cycling. Where $\overline{ESS}$ is a conservative estimation of the energy drawn for the battery as motioned in [64] and calculated in [5.15]. The average cost per MW is calculated in (23) where the battery cost in this paper is normalized to the cost used in reference [58] by dividing by $BatC_{ref}$. inequalities (5.16) and (5.17) are included to ensure that the operations of the charging and discharging rate of the BESS are within the power ratings when providing the AS capacities.

$$GG_{ydtk} = max\,(-DC \cdot ESS_{ydtk} \cdot \eta^{Dis}, 0) \quad (5.13)$$

$$DC = 0.042\left(\frac{BatC}{BatC_{ref}}\right) \quad (5.14)$$

$$\overline{ESS}_{ydtk} = ESS_{ydtk} - AP_{ydtk}^{U} - AP_{ydtk}^{R} \quad (5.15)$$

$$ESS_{ydtk} + AP_{ydtk}^{D} \leq MP_{yk} \quad (5.16)$$

$$ESS_{ydtk} - AP_{ydtk}^{U} - AP_{ydtk}^{R} \geq -MP_{yk} \quad (5.17)$$

Inequalities (5.18) and (5.19) shall be used to specify the maximum power rating and energy capacity limits, respectively. As shown in (5.18), the AS signals are considered in limit of maximum power rating of ESS.

$$\underline{MP_{yk}} \leq (ESS + AP^{D} - AP^{U} - AP^{R})_{ydtk} \leq \overline{MP_{yk}} \tag{5.18}$$

$$\underline{\xi} ME_{yk} \leq SOC_{ydtk} \leq \overline{\xi} ME_{yk} \tag{5.19}$$

Equations (5.20) is the SOC of the ESS as it is charged/discharged. Note that the regulation down (AP^{D}_{ydtk}) charges ESS, but regulation up (AP^{U}_{ydtk}) and reserve capacity (AP^{R}_{ydtk}) discharge ESS.

$$SOC_{ydtk} = SOC(y,d,t-1,k) + ESS_{ydtk} + AP^{D}_{ydtk} - AP^{U}_{ydtk} - AP^{R}_{ydtk} \tag{5.20}$$

The limit of the minimum and maximum output of the traditional generator is set out in (5.21).

$$\underline{P^{TG}_{ydtk}} \leq P^{TG}_{ydtk} \leq \overline{P^{TG}_{ydtk}} \tag{5.21}$$

The limit of the minimum and maximum of voltage magnitude and angle are set out in (5.22) and (5.23), respectively.

$$\underline{V_{k}} \leq V_{ydtk} \leq \overline{V_{k}} \tag{5.22}$$

$$\underline{\theta_{k}} \leq \theta_{ydtk} \leq \overline{\theta_{k}} \tag{5.23}$$

The planning decision variables in the complete model are summarized in Table 5.2.

Table 5.2: Operation decision varisbles in complete model

Variable	Function
BID_{ydt}	Buying/selling energy from/to market
ESS_{ydtk}	Power output of ESS
$R^{U}_{ydtk}, R^{D}_{ydtk}, R^{R}_{ydtk}$	Regulation up/down and reserve capacity, respectively
SOC_{ydtk}	State of charge of ESS
GG_{ydtk}	Depreciation cost of ESS
P^{TG}_{ydtk}	Power output of TG
E_{ydtk}	Operating cost of TG
V_{ydtk}, θ_{ydtk}	Voltage magnitude and phase angle, respectively.

5.4 Two Stage Stochastic Programming Model

The problem of obtaining the optimal planning and operation of DERs to maintain the load requirement and to maximize the profits to DSO is formulated as a two-stage mixed integer stochastic program. Stochastic programs are mathematical programs used for handling uncertainties in optimization [54]. It is required to generate scenarios for each uncertain parameter in the problem. These uncertain parameters frequently follow a distribution of probability that is recognized or can be estimated.

The most common model used in SP involve two stages. In the first stage, the decision variables must be decided upon before the stochastic variables are realized. In the second stage, the decision variables are decided based on the realization of the stochastic variables. Note that the decision variables of the second stage are affected by the decision variables made in the first stage.

In this research work, the stochastic variables are WT and market clearing price (MCP). The decision variables in the first stage are the planning decision variables subjected to (5.1)-(5.10). In the second stage, the operation decision variables subjected to (5.11) – (5.23).

According to the above discussion, the compact mathematical model of the two stage SP as follows:

$$F(x) = C^T + E[Q(x,\omega)] \tag{5.24}$$

Subject to:

$$h^R(x) = b, \qquad x \geq 0 \tag{5.25}$$

Where

$$\mathrm{Q(x,}\omega\mathrm{)=}\quad \mathrm{Max_y} \quad q_\omega^T y(\omega) \tag{5.26}$$

Subject to:

$$T_\omega x + W_\omega y(\omega) = h_\omega, \qquad \$\mathrm{y}(\omega) \geq 0, \quad \forall \omega \in \Omega \tag{5.27}$$

Let $x \in R^n$ and $y \in R^m$ are the decision variables are made in the first and second stage, respectively. The set of all realization of the stochastic variables are given by Ω, $\Omega = \Omega\{\omega_1, \omega_2, ..., \omega_s\} \subseteq R^r$, where r is number of stochastic variables representing uncertain parameter.

The first two equations represent the first stage problem, and the last two equations represent the second stage problem. In the first stage, x is the decision variable and C^T represents the cost coefficients of the objective function. Moreover, $E[Q(x,\omega)$ denotes the expected value of the optimal solution of the second stage problem. In this research work, the decision variables in the first stage are TF, AP, TI, C_{INV}^{NL}, C_{INV}^{UL}, C_{INV}^{TG}, C_{INV}^{PV}, C_{INV}^{WT}, C_{INV}^{ESS}, N_{yk}^{TG}, N_{yk}^{PV}, N_{yk}^{WT}, ME_{yk}, MP_{yk}, X_{yl}^{NL} and X_{yl}^{UL}. These decision variables are in the planning aspect and must be decided in the first stage prior the realization of stochastic variables. The cost coefficients of C^T are the investment and maintenance costs of DERs and NEP. In addition, the second line represents the constraints of the planning aspect in the first stage problem.

In the second stage problem, y is the decision variable, q^T represents the cost coefficients of the objective function, w represents the recourse matrix and T represents the transition matrix.

In this study, the decision variables in the second stage are BID_{ydt}, ESS_{ydtk}, R^{R}_{ydtk}, R^{U}_{ydtk}, R^{D}_{ydtk}, SOC_{ydtk}, P^{TG}_{ydtk}, E_{ydtk}, V_{ydtk} and θ_{ydtk}. These decision variables are in the operation aspects and must be decided in the second stage at the time of realizing uncertain parameters. The cost coefficients q^{T} are buying/selling energy from/to MCP, participating in AS market and the operation cost of thermal generator.

The planning decision variables made in the first stage are fixed prior realization of the uncertain param. After that, the operation decision variable can be optimized after realization of the uncertain parameters in the second stage, taking into account the optimal solution of the first stage to maximize DSO profits.

5.5 Case Study Description

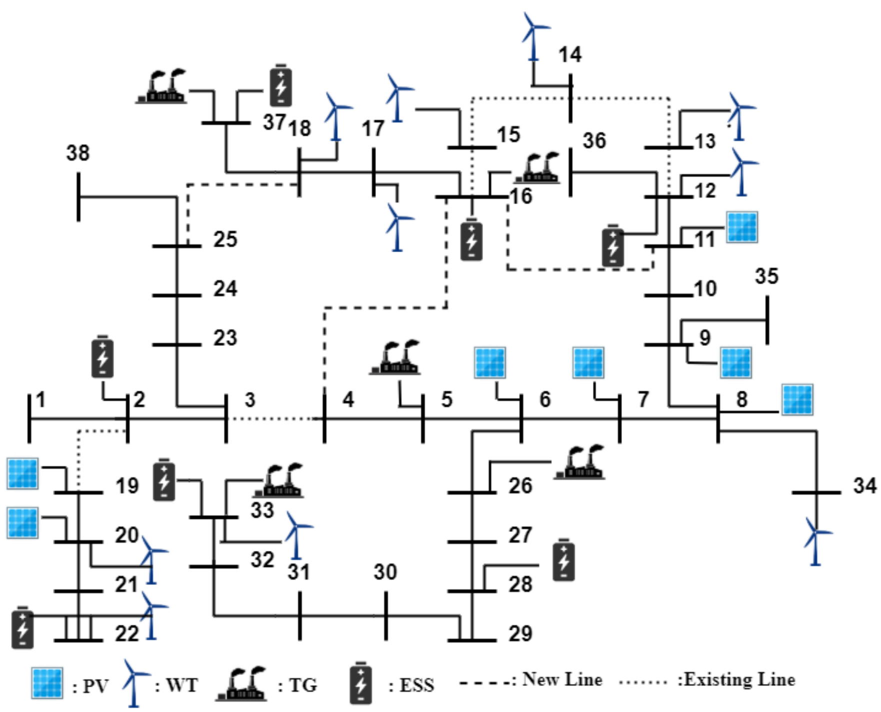

Figure 5.3: IEEE 38 bus radial distribution test system.

In this case study, the same parameter and data used in section 4.42 will be used in this case study. Figure 5.3 shows the radial a medium voltage 38 radial distribution test system with candidate location of TG, PV, and WT as well as candidate lines to be upgraded and added. The data of this network is adapted from [59].

The planning horizon for the project is eight years. In contrast to the previous case, where the load was assumed to be doubled from the beginning of the planning horizon.

The load at the first two years of the project is 4.045 MW and 2.5 MVAR. The annual load growth is assumed to be 25% in the third and fourth years, 15% in the fifth and sixth years, and 10% in the seventh and eighth years. Hence, the load is doubled at the end of the planning period and reached 8.1 MW and 5 MVAR.

It has been taken two samples for load profiles, PV, WT and MCP adapted from ERCOT [60], one sample represents summer, and one sample represents winter. Thus, the overall sample of each one of them is two samples and each sample consists of 24 hours as approached in [48]. In addition, the signals and prices of regulation up, regulation down and reserve capacities are also taken from ERCOT [60]. Figure 5.4 and Figure 5.5 show the average prices and data from ERCOT market, respectively.

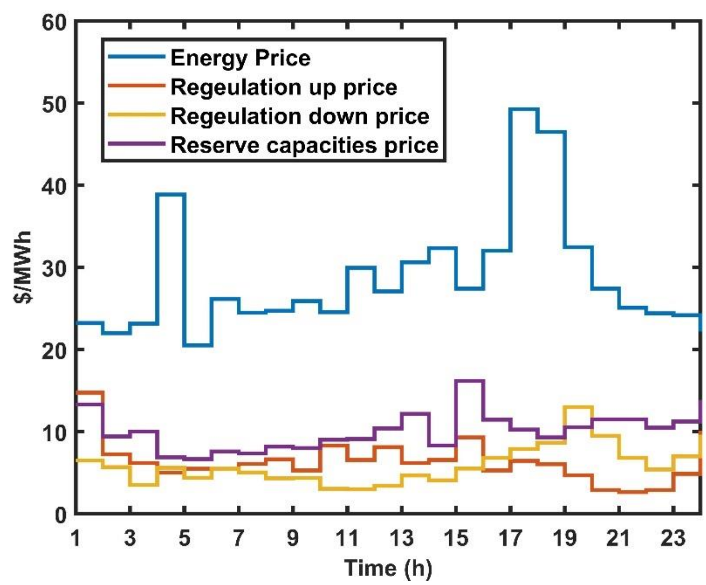

Figure 5.4: Average energy prices from ERCOT

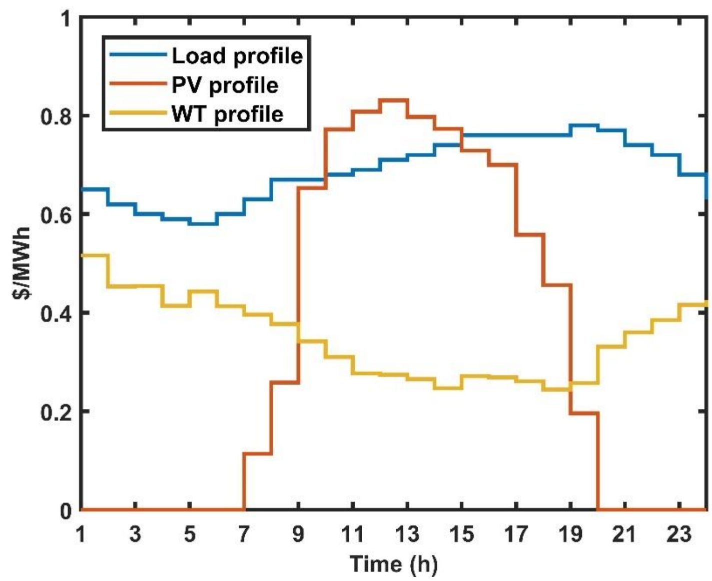

Figure 5.5: Average data from ERCOT

There are multiple uncertainties in this work which are renewable resources (PV and WT), market clearing price (MCP) and demand. However, the PV power output and load are assumed deterministic because the demand and PV power output are predictable as well as to decrease the size of the problem. On the other hand, the uncertainty of WT power output and MCP are not predictable, so two stage stochastic program is used to capture the uncertainty of wind and MCP. It has taken three scenarios for wind and MCP as approached in [48]. Hence, the total scenarios are equal to the product of the number of each set of scenarios.

In this case study, a set of preliminaries and assumptions shall be made as follows:

- The candidate buses for DERs placement are selected based on the approach set out in section 5.1, so the candidate buses for DERs are shown on Figure 5.3.
- The investment in installing new DERs, adding new lines, and upgrading existing lines are assumed to be made every two years the first year, third year, fifth year, and seventh year.
- PV and WT experience uniform wind speed and solar radiation in all buses.
- The candidate lines to be upgraded are selected on the basis of the approach set out in Section 4.2, so the candidate lines are shown on Figure 5.3.
- The candidate construction of new line between two buses are selected arbitrary as demonstrated on Figure 5.3.

- The upper and lower bus voltages need to be maintained within 1.05 and 0.95, respectively.
- Discount rate considered in this work is 7%.

The capital cost and maintenance cost of the renewable resources and ESS are adapted from [62], and the capital cost and maintenance cost of TG is taken from [63]. The technical and economic parameters of RESs and ESS are provided in Table 5.3. The upgraded and added new line costs are adapted from [40][52] and shown in the **Error! Reference source not found.**.

Table 5.3: The technical and economic parameters of DERs

Resource	Capital cost	Annual O&M cost	Lifespan
TG	318 $/kw	61.32 $/kw	20
PV	1343 $/kw	12 $/kw	25
WT	950 $/kw	27 $/kw	25
ESS	175 $/kw	2 $/MWh	10
	225 $/kwh	4.00 $/kw	

The cost coefficients (A, B and C) of the conventional generation units are $0.09\$/h(MW)^2, 10\$/h(MW)$ and $120\$$ respectively as adapted from [64]. The capital cost of adding/upgrading lines is 86100 $/MVA and adapted from [52].

5.6 Base Case Results

The proposed ADN model's performance is evaluated in situations where the DSO has multiple alternatives, such as purchasing/selling electricity from/to the wholesale market, installing DERs, constructing new lines, and/or upgrading existing lines, to maximize profits while meeting load requirements. These results have been obtained for solving (5.1) – (5.23) with the following linearized model for the thermal production cost, distribution network model, and network expansion planning presented in section 3.2.3, section 4.1, and section 4.2, respectively.

As the investment in installing DERs and upgrading/adding lines to the existing network is assumed to take place once every two years, so the capacity of DERs and network will be changed every two years as shown in Figure 5.7. Figure 5.6 demonstrates sum of the total profits (TP), salvage value (SV), and total investment costs (TI) at the end of each two years.

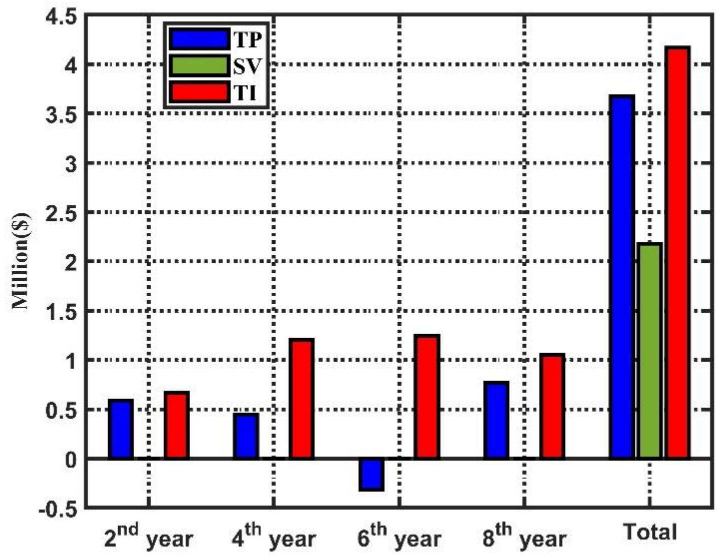

Figure 5.6: The optimal payoff in base case.

Figure 5.7 shows the sizing of the DERs over the planning horizon. The optimal results show that ESS (5.392 MWh) is the most effective resource to maximize the total payoff to DSO. It is expected that the ESS is the most attractive resource because ESS is used for three purposes in the proposed model. The first purpose is to participate in AS, the second purpose is to help to overcome the variation of RESs and the third purpose to charge/discharge to maximize the overall payoff and meet the demand requirements. However, TG (2.54 MWh) and WT (2.467 MWh) are selected over PV (0 MWh).

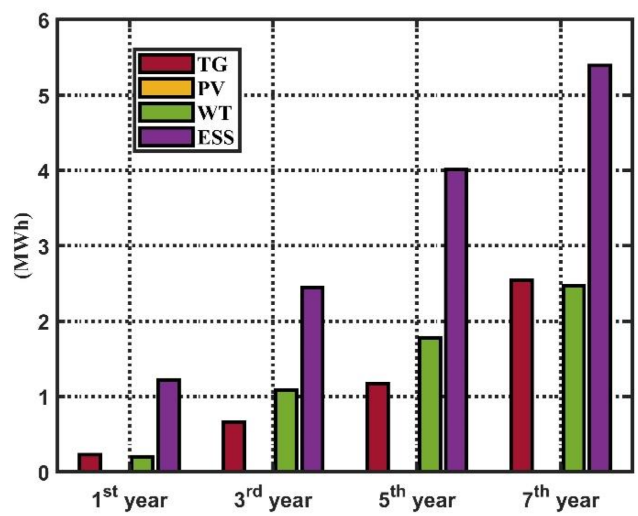

Figure 5.7: The optimal capacity of DERs in base case.

According to the results, the optimal location and sizing of DERs are summarized in the Table 5.4.

Table 5.4: Optimal location of DERs in the base case

No of Bus	1st year	3rd year	5th year	7th year
PV (MWh)				
Bus 26	0	0	0	1.371
Bus 36	0	0.428	0.939	0.939
Bus 37	0.23	0.23	0.23	0.23
WT (MWh)				
Bus 12	0	0	0	0.24
Bus 13	0	0	0.2	0.2
Bus 14	0	0.223	0.512	0.512
Bus 15	0	0.261	0.261	0.261
Bus 20	0	0.2	0.2	0.2
Bus 22	0.2	0.4	0.4	0.6
Bus 34	0	0	0.2	0.454
ESS (MW)				
Bus 2	0	0	0	0.217
Bus 12	0.395	1.039	1.345	1.562
Bus 16	0.2	0.417	0.417	0.417
Bus 22	0.2	0.4	0.4	0.4
Bus 28	0	0	0.839	1.41
Bus 33	0	0	0.2	0.2
Bus 37	0.205	0.405	0.405	0.405
ESS (MWh)				
Bus 2	0	0	0	0.217
Bus 12	0.502	1.039	1.565	1.96
Bus 16	0.258	0.458	0.458	0.458
Bus 22	0.2	0.492	0.492	0.492
Bus 28	0	0	0.839	1.41
Bus 33	0	0	0.2	0.2
Bus 37	0.255	0.455	0.455	0.655

The selected line to be added and upgraded is shown in Table 5.5. It is obvious from the results; the optimal solution is more interested in installing DGs and ESS rather than enhancing the distribution network. In addition, installing DERs in distribution network contributes to postpone upgrading the network.

Table 5.5: Selected lines to be added/upgraded

Selected new Line	
No	**Year**
Line 4-16	7^{th} year
Selected Upgrading Line	
No	**Year**
Line 2-19	5^{th} year

5.7 Sensitivity Analysis

The proposed ADN model is evaluated in five various cases following:

- Effect of network expansion planning (NEP).
- Effect of renewable energy resources (RESs).
- Effect of energy storage system (ESS).
- Effect of ancillary services (AS).
- Effect of dynamic planning methodology (DP).

In each case, the same parameters are used as in the previous section to test the effectiveness of network expansion planning, distribution generators, energy storage system, ancillary services, and dynamic planning methodology in the proposed model.

5.7.1 Effect of NEP

In this subsection, the NEP is not taken into the planning optimization to study the effect of NEP in the proposed model. The optimal payoff over the planning horizon is shown in Figure 5.8. The results show that the optimal profits reduced by 9.7% from $ 3.675 million to $ 3.3167 million compared to the base case results addressed in Sec. 5.6.

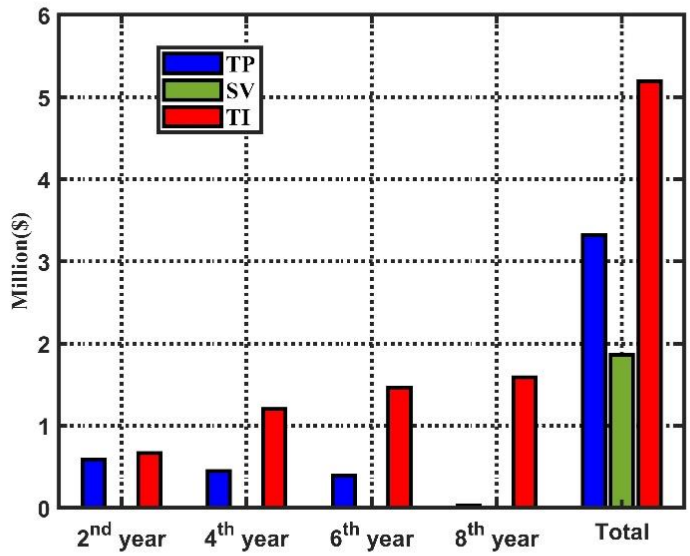

Figure 5.8: Optimal payoff in NEP case.

The optimal capacity of DERs are demonstrated in Figure 5.9 and the optimal location of DERs is available in Appendix.

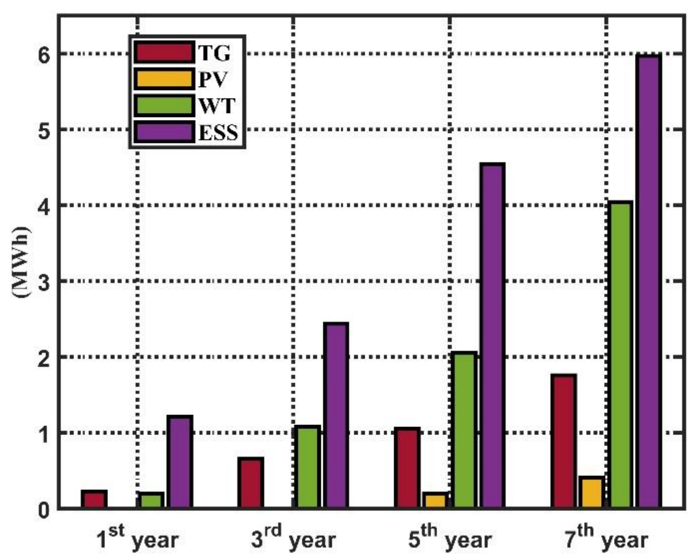

Figure 5.9: Optimal capacity of DERs in NEP effect.

In this case study, the RESs and ESS are increased, however the TG is reduced compared to the base case results. From the obtained results, increasing the RESs required to increase the ESS to overcome the challenges caused by RESs as enhancing the network is not considered.

5.7.2 Effect of RESs

In this subsection, it is assumed that ESS and TG are considered as DERs. The optimal profits and capacity of ESS and TG over the planning horizon are demonstrated in the Figure 5.10 and Figure 5.11, respectively. The optimal location of ESS and TG are available in Appendix.

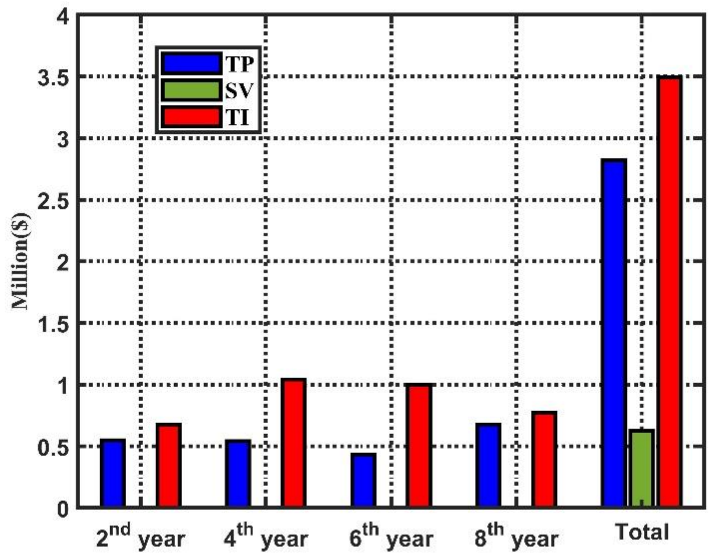

Figure 5.10: Optimal payoff in DGs effect.

As can be observed, the optimal payoffs are decreased by 23.18% $ 3.675 million to $ 2.82 million compared to the base case.

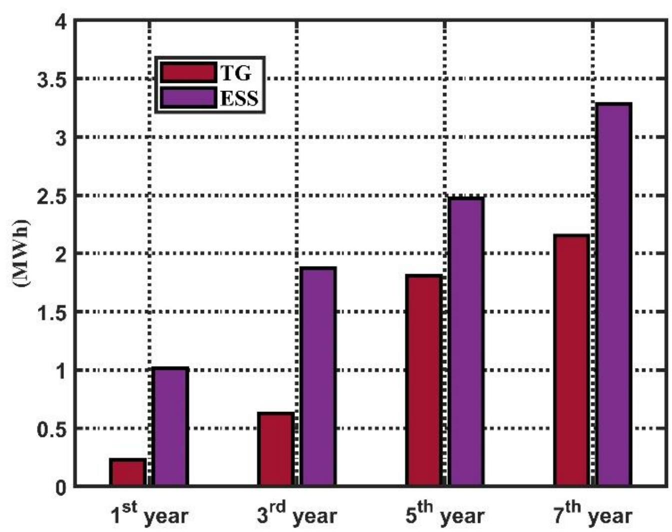

Figure 5.11: Optimal capacity in RESs effect

It is interesting to note that the total investment cost (TI) is increased in this subsection, but the salvage value (SV)is decreased compared to the base case. The explanation behind this is that the lifetime of the ESS is short relative to the DGs, so the salvage value would be low.

It is interesting to notice that the capacity and power rating of ESS are decreased by 30.77% and 53%, respectively compared to the base case. It has been stated in this research work, one of the purposes of considering ESS in the model is to overcome the challenges caused by RESs to maintain the network constraints. In addition to that, TG is considered with ESS in this case study where TG is controllable compared to RESs. Thus, ESS will be less attractive in the absence of RESs as TG is controllable.

It is noticeable in the Figure 5.10, the highest investment occurred at the end of fourth because of the huge investment in enhance the network as shown in the Table 5.6. Moreover, the fourth year is expected to have the highest investment because of the load growth, so DSO needs to invest to enhance the existing network.

Table 5.6: Selected lines in DGs effect

Selected new Line	
No	**Year**
Line 11-16	3rd year
Line 25-18	3rd year
Line 4-16	3rd year
Selected Upgrading Line	
No	**Year**
Line 16-17	1st year

5.7.3 Effect of ESS

ESS is used in this model to provide AS, to maximize the profits to DSO and to overcome the challenges caused by RESs to maintain the network constraints. However, the ESS is not considered in this subsection, so AS is also not taken into account. The optimal payoff and optimal capacity of DGs during the planning horizon is demonstrated in the Figure 5.12 and Figure 5.13, respectively. The optimal location of DGs in this subsection is available in Appendix.

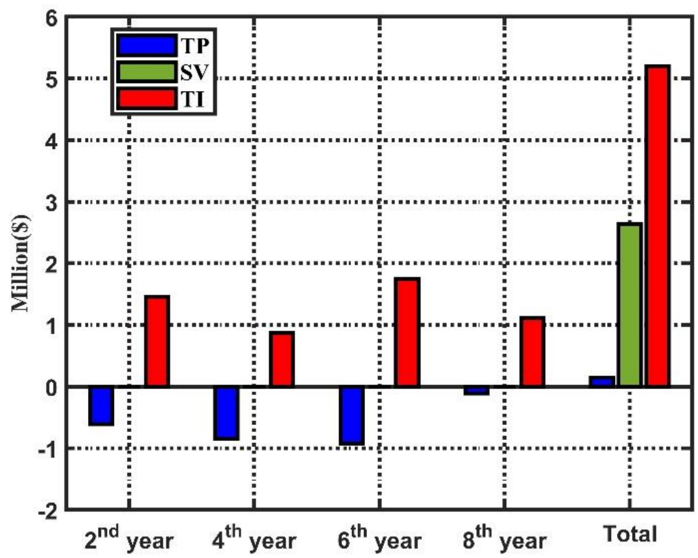

Figure 5.12: Optimal payoff in ESS effect.

The payoff is decreased significantly by 96% from $ 3.675 million to $ 0.1469 million. The high dropped in payoff can be explained by three reasons. First reason, in the absence of ESS, the DSO cannot provide AS to the grid and participate in AS market. Second reason, more TG are installed in the system to meet the demand as shown in the Figure 5.13. From the obtaining results, in the absence of ESS, the TG is more suitable and controllable than RESs to meet the load requirements. However, the operating cost of TG is much higher than ESS, so the operating costs effects the overall payoff to the DSO.

Moreover, there is a need to upgrade the existing network as shown in the Table 5.7. Thus, the investment cost in the absence of DGs is increased by 28.85% from $ 4.166 million to $ 5.20 million compared to the base case.

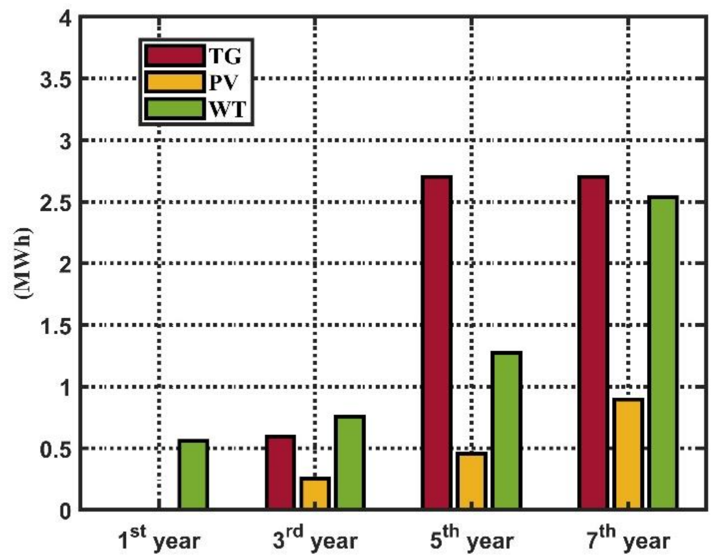

Figure 5.13: Optimal capacity of DGs in ESS effect.

In the absence of ESS, the number of added and upgraded lines are increased in this subsection as shown in Table 5.7.

Table 5.7: Selected lines in ESS effect

Selected new Line	
No	**Year**
Line 11-16	1st year
Line 4-16	1st year
Line 25-18	1st year
Selected Upgrading Line	
No	**Year**
Line 17-18	1st year
Line 2-19	3rd year
Line 19-20	5th year
Line 20-21	5th year
Line 21-22	5th year

5.7.4 Effect of AS

DSO participates in AS market to provide regulation up, regulation down and reserve using ESS. In this subsection, the AS is not considered to study the impact of AS on the overall payoffs and on the capacity of DERs. The optimal payoff and the capacity of DERs is shown in the Figure 5.14 and Figure 5.15, respectively. The optimal location of DERs in this subsection is available in Appendix.

The overall profits to the DSO is decreased by 69.23% from \$ 3.675 million to \$ 1.31 million. The total investment cost is increased by 4.37% in this subsection because AS is not taken into account, so it is necessary to invest in NEP to maintain voltage constraints and DERs to meet the load requirements and maximize the total payoff.

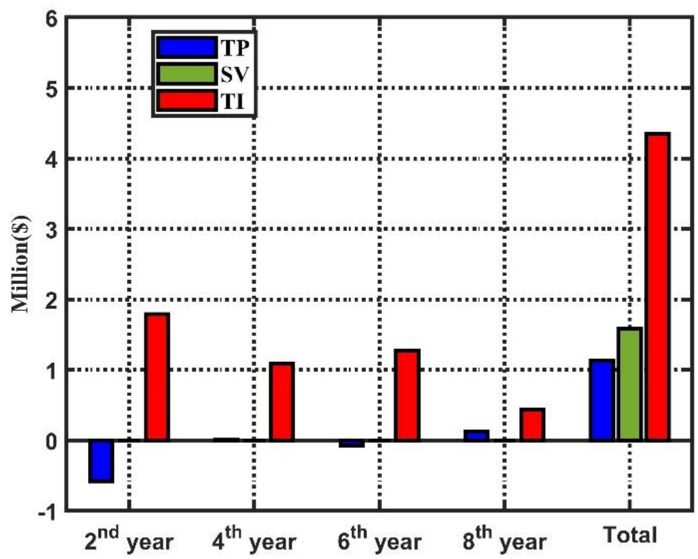

Figure 5.14: Optimal payoff in AS effect.

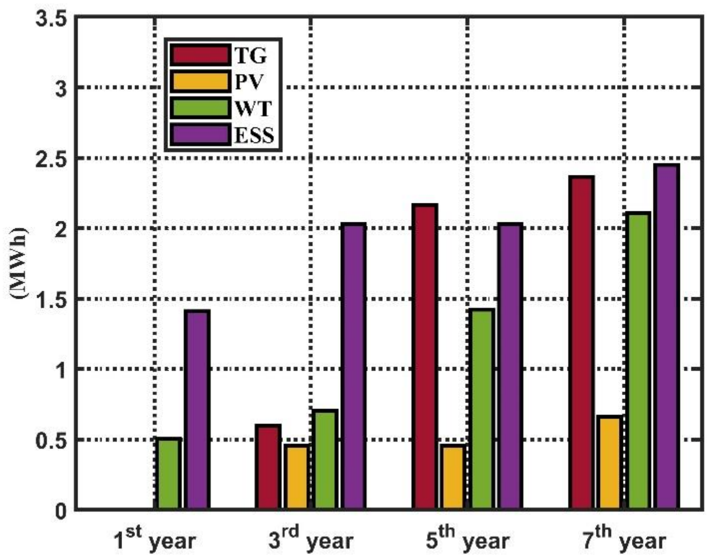

Figure 5.15: Optimal capacity of DERs in AS effect.

It is interesting to notice that the power rating and capacity of ESS are dropped by 55.15% and 54.56%, respectively. These results indicate that participation in the AS market contributes to an increase in ESS capacity. In addition to that, AS contributes to postpone enhancing the network because AS helps to maintain network constrains such as voltage magnitude and phase angles. Thus, in the absence of AS, selected lines to be upgraded and added are increased as demonstrated in Table 5.8.

Table 5.8: Selected lines in AS effect.

Selected new Line	
No	**Year**
Line 11-16	1st year
Line 4-16	1st year
Line 25-18	1st year
Selected Upgrading Line	
No	**Year**
Line 17-18	1st year
Line 2-19	3rd year
Line 19-20	5th year

5.7.5 Effect of DP

In this subsection, a SP methodology is used to solve the problem to show how the results are affected compared to DP methodology. It follows the same procedure presented in Section II-G, but the sizing of DERs and selected new/upgrading lines is solved only one time based on the estimated load at the end of planning period. After that, the same selected DERs and new/upgrading lines are used with estimated load for each year from the beginning to the end of planning period.

The optimal payoff and the capacity of DERs is shown in the Figure 5.16 and Figure 5.17, respectively. The optimal location of DERs in this subsection is available in Appendix. The overall payoff to the DSO is decreased by 2% from $ 3.675 million to $ 3.6018 million.

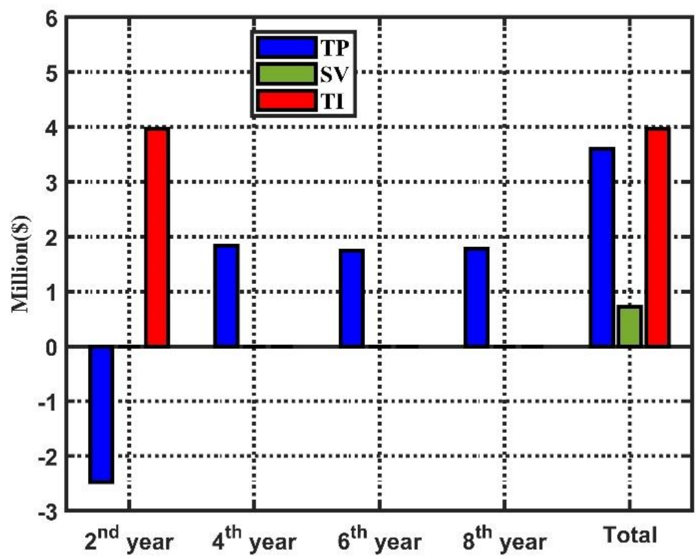

Figure 5.16: Optimal payoff in DP effect.

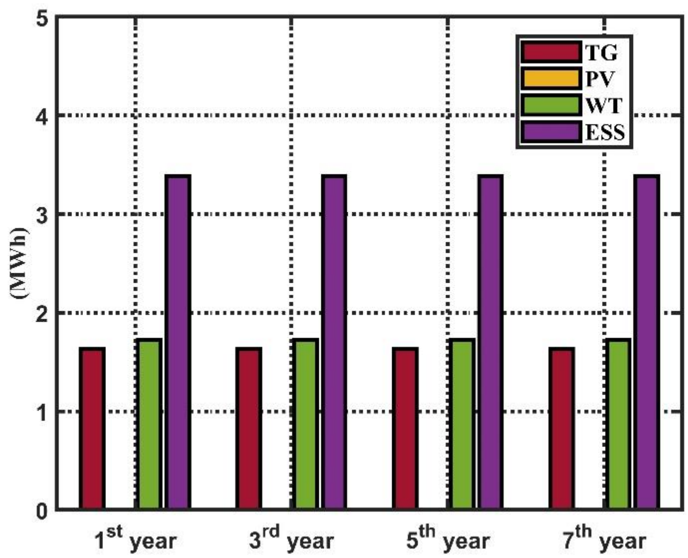

Figure 5.17: Optimal capacity of DERs in DP effect.

As well known, that, the SV depends on the lifetime of assets, so it is expected the SV will be decreased in this subsection dramatically. In this subsection, the SV is dropped by 67.14% compared to the base case because all investments for DERs and NEP are made in the first year of the planning period.

In this subsection, there is one line is added and two lines are upgraded as shown in Table 5.9.

Table 5.9: Selected lines in DP effect.

Selected new Line	
No	**Year**
Line 4-16	1^{st} year
Selected Upgrading Line	
No	**Year**
Line 15-16	1^{st} year
Line 2-19	1^{st} year

Table 5.10 summarizes the effectiveness of various cases compared to the base case on the optimal results including TP, SV, TI, and capacity of DERs.

Table 5.10: Summarizes the effectiveness of various cases

	A	B	C	D	E
Optimal Payoff					
TP	-9.70%	-23.18%	-96.0%	-69.23%	-2.00%
SV	-14.96%	71.73	-20.98%	-27.49%	-67.14%
TI	24.63%	-16.12%	28.85%	4.37%	-4.72%
Optimal Capacity of DERs					
TG (MWh)	-30.63%	-15.24%	6.45%	6.89%	-35.83%
PV (MWh)	0.416	-	0.896	0.66	0
WT (MWh)	63.76%	-	-16.17	-16.17%	-30.12%
ESS (MW)	14.75%	-30.77%	-	-55.15%	-41.92%
ESS (MWh)	10.78%	-53.00%	-	-54.56%	-37.18%

Notice that, there is no PV installation (0 MW) in the base case, so it is not possible to find the increase/decrease percentage in the sensitivity analysis compared to the base case. Hence, the numbers for PV shown on Table 5.10 are not percentage, they are the capacity of PV in each case.

CHAPTER 6

CONCLUSION AND FUURE WORK

In this thesis, a DP model for a market-based assessment of potential investment opportunities in the ADN is discussed. DP methodology is used to respond to the load growth in which the installation of DERs and the addition/upgrading of new/existing lines are considered as an economic alternative for the DSO. The AS is considered by bidding regulation up/down and reserve capacities. Two stage stochastic programming is used to address uncertainty of MCP and the production of WT. The proposed model is formulated as a mixed-integer stochastic linear program. The main purpose of this model is to maximize the profits to DSO. The proposed model consists of planning and operation aspects and solve them simultaneously. The optimal sizing and location of ADN’s resources and network expansion are taken into consideration in the planning aspect. The optimal operation of the system to maximize the profits and maintain the network constraints is considered in the operation aspects. In addition, The model provides the ability to incorporate the effects of regulation capacities and signals in the network voltages and lines limits.

The results show that installing DERs and upgrading existing network are required to maximize the profits and meet the load growth. In addition, sensitivity analysis to evaluate effectiveness of NEP, RESs, ESS, AS, and DP are carried out. It is shown that ESS has the highest effect on the optimal profits to DSO while DP has the lowest effect. In addition, participating in AS market makes ESS more attractive to the DSO.

In the future work, demand response (DR) will be considered to turn energy users into virtual power plants by modifying their energy consumption during specific times to maintain the network constraints and alleviate stress on the grid. In addition, the water desalination operation will be considered as DR. As well known, freshwater resources gradually decrease, desalination capacities throughout the world are expected to increase. Nevertheless, high electricity consumption costs prevent the development of desalination plants.

A promising solution to minimize a part of these costs is to request water desalination system operators (WDSO) to offer the flexibility of their water desalination plants. Thus, the interaction between DSO and WDSO will be discussed to optimize the operation of desalination plants and participation in the electricity DR.

References

[1] International Renewable Energy Agency, 2018. [online]. available: https://www.irena.org/, access date = 2019-01-2.

[2] M. Coddington, D. Sciano, and J. Fuller, "Change in brooklyn and queens: How new york? s reforming the energy vision program and con edison are reshaping electric distribution planning," IEEE Power and Energy Magazine, vol. 15, no. 2, pp. 40–47, 2017.

[3] P. Andrianesis, M. Caramanis, R. D. Masiello, R. D. Tabors, and S. Bahramirad, "Locational marginal value of distributed energy resources as non-wires alternatives," IEEE Transactions on Smart Grid, vol. 11, no. 1, pp. 270–280, 2019.

[4] X. Liang, "Emerging power quality challenges due to integration of renewable energy sources," in IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 855–866, March-April 2017.

[5] A. A. M. S. V. Telukunta, J. Pradhan and S. G. Srivani, "Protection challenges under bulk penetration of renewable energy resources in power systems: A review," in CSEE Journal of Power and Energy Systems, vol. 3, no. 4, pp. 365–379, Dec 2017.

[6] B. Mohandes, M. S. El Moursi, N. Hatziargyriou, and S. El Khatib, "A review of power system flexibility with high penetration of renewables," IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 3140–3155, 2019.

[7] M. Huber, D. Dimkova, and T. Hamacher, "Integration of wind and solar power in europe: Assessment of flexibility requirements," Energy, vol. 69, pp. 236–246, 2014.

[8] M. Fazeli, J. B. Ekanayake, P. M. Holland, and P. Igic, "Exploiting pv inverters to support local voltage—a small-signal model," IEEE Transactions on Energy Conversion, vol. 29, no. 2, pp. 453–462, 2014.

[9] J. T. F. Mohamad and H. Abunima, "Multi-objective optimization of solar/wind penetration in power generation systems," in IEEE Access, vol. 7, pp. 169 094–169 106, 2019.

[10] R. K. S. Bhattarai and P. Piya, "Reliability modelling of compressed air energy storage for adequacy assessment of wind integrated power system," in IET Generation, Transmission Distribution, vol. 13, no. 19, pp. 4443–4450, Oct 2019.

[11] A. J. Headley and D. A. Copp, "Energy storage sizing for grid compatibility of intermittent renewable resources: A california case study," Energy, p. 117310, 2020.

[12] L. Chen, H. Wang, D. Li, K. Huang, and Q. Ai, "Two-stage stochastic programming method for multi-energy microgrid system," pp. 1129– 1135, 2020.

[13] A. Khayatian, M. Barati, and G. J. Lim, "Integrated microgrid expansion planning in electricity market with uncertainty," IEEE Transactions on Power Systems, vol. 33, no. 4, pp. 3634–3643, 2017.

[14] B. Zhao, A. J. Conejo, and R. Sioshansi, “Coordinated expansion planning of natural gas and electric power systems,” IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3064–3075, 2017.

[15] S. Montoya-Bueno, J. I. Muoz, and J. Contreras, “A stochastic investment model for renewable generation in distribution systems,” IEEE Transactions on Sustainable Energy, vol. 6, no. 4, pp. 1466–1474, 2015.

[16] M. Jooshaki, A. Abbaspour, M. Fotuhi-Firuzabad, H. Farzin, M. MoeiniAghtaie, and M. Lehtonen, “A milp model for incorporating reliability indices in distribution system expansion planning,” IEEE Transactions on Power Systems, vol. 34, no. 3, pp. 2453–2456, 2019.

[17] G. Munoz-Delgado, J. Contreras, and J. M. Arroyo, “Distribution system expansion planning considering non-utility-owned dg and an independent distribution system operator,” IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 2588–2597, 2019.

[18] S. Guo, T.-M. Choi, B. Shen, and S. Jung, “Coordination and enhancement schemes for quick response mass customization supply chains with consumer returns and salvage value considerations,” IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2017.

[19] X. Huang, J.-W. Gu, W.-K. Ching, and T.-K. Siu, “Impact of secondary market on consumer return policies and supply chain coordination,” Omega, vol. 45, pp. 57–70, 2014.

[20] A. M. Pirbazari, "Ancillary services definitions, markets and practices in the world," in 2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010, pp. 32-36.

[21] X. He, N. Keyaerts, I. Azevedo, L. Meeus, L. Hancher, and J.-M. Glachant, "How to engage consumers in demand response: A contract perspective," Utilities Policy, vol. 27, pp. 108-122, 2013/12/01/ 2013.

[22] F. R. Islam and H. R. Pota, "Integrating Smart PHEVs in Future Smart Grid," in Renewable Energy Integration: Challenges and Solutions, J. Hossain and A. Mahmud, Eds., ed Singapore: Springer Singapore, 2014, pp. 239-258.

[23] B. Xu, A. Oudalov, J. Poland, A. Ulbig, and G. Andersson, "BESS Control Strategies for Participating in Grid Frequency Regulation," IFAC Proceedings Volumes, vol. 47, pp. 4024-4029, 2014/01/01/ 2014.

[24] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, "Value Analysis of Battery Energy Storage Applications in Power Systems," in 2006 IEEE PES Power Systems Conference and Exposition, 2006, pp. 2206-2211.

[25] S. J. Lee, J. H. Kim, C. H. Kim, S. K. Kim, E. S. Kim, D. U. Kim, et al., "Coordinated Control Algorithm for Distributed Battery Energy Storage Systems for Mitigating Voltage and Frequency Deviations," IEEE Transactions on Smart Grid, vol. 7, pp. 1713-1722, 2016.

[26] G. Heffner, "Loads providing ancillary services: Review of international experience," 2008.

[27] A. M. Pirbazari, “Ancillary services definitions, markets and practices in the world,” pp. 32–36, 2010.
[28] X. He, N. Keyaerts, I. Azevedo, L. Meeus, L. Hancher, and J.-M. Glachant, “How to engage consumers in demand response: A contract perspective,” Utilities Policy, vol. 27, pp. 108–122, 2013.
[29] J. Tan and Y. Zhang, “Coordinated control strategy of a battery energy storage system to support a wind power plant providing multi-timescale frequency ancillary services,” IEEE Transactions on Sustainable Energy, vol. 8, no. 3, pp. 1140–1153, 2017.
[30] M. A. Awadallah and B. Venkatesh, “Energy storage in distribution system planning and operation: current status and outstanding challenges,” Canadian Journal of Electrical and Computer Engineering, vol. 42, no. 1, pp. 10–19, 2019.
[31] Y. J. A. Zhang, C. Zhao, W. Tang, and S. H. Low, “Profit-maximizing planning and control of battery energy storage systems for primary frequency control,” IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 712–723, 2016.
[32] A. muqbel, A. Aldik, A. T. Al-Awami, and F. Alismail, “Fuzzy optimization-based sizing of a battery energy storage system for participating in ancillary services markets,” pp. 1–7, 2018.
[33] H. Haghighat and B. Zeng, “Stochastic and chance-constrained conic distribution system expansion planning using bilinear benders decomposition,” IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 2696– 2705, 2017.
[34] S. M. Mazhari, H. Monsef, and R. Romero, “A multi-objective distribution system expansion planning incorporating customer choices on reliability,” IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1330–1340, 2015.
[35] N. Koutsoukis, P. Georgilakis, and N. Hatziargyriou, “Active distribution network planning based on a hybrid genetic algorithm-nonlinear programming method,” CIRED-Open Access Proceedings Journal, vol. 2017, no. 1, pp. 2065–2068, 2017.
[36] M. Sedghi, A. Ahmadian, and M. Aliakbar-Golkar, “Optimal storage planning in active distribution network considering uncertainty of wind power distributed generation,” IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 304–316, Jan 2016.
[37] M. Nick, R. Cherkaoui, and M. Paolone, “Optimal planning of distributed energy storage systems in active distribution networks embedding grid reconfiguration,” IEEE Transactions on Power Systems, vol. 33, no. 2, pp. 1577–1590, 2018.
[38] L. Zhao, Y. Huang, Q. Dai, L. Yang, F. Chen, L. Wang, K. Sun, J. Huang, and Z. Lin, “Multistage active distribution network planning with restricted operation scenario selection,” IEEE Access, vol. 7, pp. 121 067–121 080, 2019.
[39] K. Masteri, B. Venkatesh, and W. Freitas, “A fuzzy optimization model for distribution system asset planning with energy storage,” IEEE transactions on power systems, vol. 33, no. 5, pp. 5114–5123, 2018.
[40] B. Jeddi, V. Vahidinasab, P. Ramezanpour, J. Aghaei, M. Shafiekhah, and J. P. Catalão, “ optimization framework for dynamic distributed energy resources planning in distribution

networks," International Journal of Electrical Power & Energy Systems, vol. 110, pp. 419–433, 2019.

[41] H. Xing and X. Sun, "Distributed generation locating and sizing in active distribution network considering network reconfiguration," IEEE Access, vol. 5, pp. 14 768–14 774, 2017.

[42] H. Xing, H. Fan, X. Sun, S. Hong, and H. Cheng, "Optimal siting and sizing of distributed renewable energy in an active distribution network," CSEE journal of power and energy systems, vol. 4, no. 3, pp. 380–387, 2018.

[43] A. Ehsan, M. Cheng, and Q. Yang, "Scenario-based planning of active distribution systems under uncertainties of renewable generation and electricity demand," CSEE Journal of Power and Energy Systems, vol. 5, no. 1, pp. 56–62, 2019.

[44] C. Zhang, J. Li, Y. J. Zhang, and Z. Xu, "Data-driven sizing planning of renewable distributed generation in distribution networks with optimality guarantee," IEEE Transactions on Sustainable Energy, 2019.

[45] M. Asensio, G. Muñoz-Delgado, and J. Contreras, "A bi-level approach to distribution network and renewable energy expansion planning considering demand response," IEEE Transactions on Power Systems, vol. 32, no. 6, pp. 4298–4309, Nov 2017.

[46] A. Zare, C. Chung, J. Zhan, and S. O. Faried, "A distributionally robust chance-constrained milp model for multistage distribution system planning with uncertain renewables and loads," IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 5248–5262, 2018.

[47] S. Sannigrahi, S. R. Ghatak, and P. Acharjee, "Multi-scenario based bilevel coordinated planning of active distribution system under uncertain environment," IEEE Transactions on Industry Applications, vol. 56, no. 1, pp. 850–863, 2019.

[48] M. Jooshaki, H. Farzin, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Lehtonen, "A model for stochastic planning of distribution network and autonomous dg units," IEEE Transactions on Industrial Informatics, vol. 16, no. 6, pp. 3685–3696, 2019.

[49] J. Qiu, Z. Xu, Y. Zheng, D. Wang, and Z. Y. Dong, "Distributed generation and energy storage system planning for a distribution system operator," IET Renewable Power Generation, vol. 12, no. 12, pp. 1345– 1353, 2018.

[50] A. Ehsan and Q. Yang, "Coordinated investment planning of distributed multi-type stochastic generation and battery storage in active distribution networks," IEEE Transactions on Sustainable Energy, vol. 10, no. 4, pp. 1813–1822, Oct 2019.

[51] S. F. Contreras, C. A. Cortes, and J. M. Myrzik, "Optimal microgrid planning for enhancing ancillary service provision," Journal of Modern Power Systems and Clean Energy, vol. 7, no. 4, pp. 862–875, 2019.

[52] Home-Ortiz, Juan M., Mahdi Pourakbari-Kasmaei, Matti Lehtonen, and José Roberto Sanches Mantovani. "A mixed integer conic model for distribution expansion planning: Matheuristic approach." IEEE Transactions on Smart Grid 11, no. 5 (2020): 3932-3943.

[53] J. Yang, N. Zhang, C. Kang, and Q. Xia, "A state-independent linear power flow model with accurate estimation of voltage magnitude," IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3607–3617, Sep. 2017.

[54] A. T. Al-Awami and M. A. El-Sharkawi, "Coordinated trading of wind and thermal energy," IEEE Transactions on Sustainable Energy, vol. 2, no. 3, pp. 277–287, July 2011.

[55] M. Carrion and J. M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," IEEE Transactions on Power Systems, vol. 21, no. 3, pp. 1371–1378, Aug 2006.

[56] J. Aghaei, N. Amjady, A. Baharvandi, and M.-A. Akbari, "Generationand transmission expansion planning: Milp–based probabilistic model,"IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1592–1601,2014.

[57] A. Jahid, M. K. H. Monju, M. E. Hossain, and M. F. Hossain, "Renewable energy assisted cost aware sustainable off-grid base stations with energy cooperation," IEEE Access, vol. 6, pp. 60 900–60 920, 2018.

[58] E. S. A. M. M. A. Aldik, A. T. Al-Awami and M. Shahidehpour, "A planning model for electric vehicle aggregators providing ancillary services," in IEEE Access, vol. 6, pp. 70 685–70 697, 2018.

[59] D. Singh, R. K. Misra, and D. Singh, "Effect of load models in distributed generation planning," IEEE Transactions on Power Systems, vol. 22, no. 4, pp. 2204–2212, 2007.

[60] E. R. C. of Texas. Accessed: 14-Apr-2019., "[online]. available: www.ercot.com/."

[61] N. R. E. L. A. 02-Dec-2019., "[online]. available: https://www.nrel.gov/."

[62] R. Li, W. Wang, and M. Xia, "Cooperative planning of active distribution system with renewable energy sources and energy storage systems," IEEE Access, vol. 6, pp. 5916–5926, 2018.

[63] N. Khalesi, N. Rezaei, and M.-R. Haghifam, "Dg allocation with application of dynamic programming for loss reduction and reliability improvement," International Journal of Electrical Power Energy Systems, vol. 33, no. 2, pp. 288–295, 2011.

[64] A. T. Al-Awami, N. A. Amleh, and A. M. Muqbel, "Optimal demand response bidding and pricing mechanism with fuzzy optimization: Application for a virtual power plant," IEEE Transactions on Industry Applications, vol. 53, no. 5, pp. 5051–5061, 2017.

Appendix

The optimal location and sizing of DERs in various cases in sensitivity analysis is shown in the Table 6.1.

Table 6.1: Optimal location and sizing of DERs in seneitivity analysis cases

Case	No of Bus	1^{st} year	3^{rd} year	5^{th} year	7^{th} year
TG (MWh)					
Effect of NEP	**Bus 16**	0	0.428	0.828	1.532
	Bus 37	0.23	0.23	0.23	0.23
Effect of RESs	**Bus 11**	0	0.2	1.18	1.523
	Bus 16	0.23	0.23	0.23	0.23
	Bus 22	0	0.2	0.4	0.4
Effect of ESS	**Bus 30**	0	0	1.447	1.447
	Bus 33	0	0.596	0.596	0.596
	Bus 36	0	0	0.661	0.661
Effect of AS	**Bus 28**	0	0	1.57	1.57
	Bus 36	0	0.596	0.596	0.795
Effect of DP	**Bus 26**	1.422	1.422	1.422	1.422
	Bus 37	0.208	0.208	0.208	0.208
PV (MWh)					
Effect of NEP	**Bus 19**	0	0	0.2	0.416
Effect of ESS	**Bus 12**	0	0.256	0.256	0.256
	Bus 17	0	0	0	0.24
	Bus 19	0	0	0	0.2
	Bus 22	0	0	0.2	0.2
Effect of AS	**Bus 12**	0	0.256	0.256	0.256
	Bus 17	0	0	0	0.204
	Bus 22	0	0.2	0.2	0.2
Wind (MWh)					
Effect of NEP	**Bus 12**	0	0	0	0.363
	Bus 13	0	0	0.2	0.2
	Bus 14	0	0.223	0.512	0.512
	Bus 15	0	0.261	0.261	0.261
	Bus 20	0	0.2	0.488	1.118
	Bus 22	0.2	0.4	0.4	0.6
	Bus 34	0	0	0.2	0.986
Effect of ESS	**Bus 13**	0.2	0.2	0.516	1.376
	Bus 22	0.358	0.358	0.358	0.558

	Bus 33	0	0	0.2	0.2
	Bus 37	0	0.2	0.2	0.4
Effect of AS	**Bus 13**	0.2	0.2	0.516	0.852
	Bus 22	0.303	0.303	0.506	0.856
	Bus 33	0	0	0.2	0.2
	Bus 37	0	0.2	0.2	0.2
Effect of DP	**Bus 12**	0.2	0.2	0.2	0.2
	Bus 13	0.2	0.2	0.2	0.2
	Bus 14	0.444	0.444	0.444	0.444
	Bus 22	0.401	0.401	0.401	0.401
	Bus 34	0.479	0.479	0.479	0.479
ESS (MW)					
Effect of NEP	**Bus 2**	0	0	0	0.499
	Bus 12	0.395	1.039	1.296	1.496
	Bus 16	0.2	0.417	0.417	0.417
	Bus 22	0.2	0.4	0.4	0.6
	Bus 28	0	0	1.024	1.474
	Bus 33	0	0	0.2	0.2
	Bus 37	0.205	0.405	0.405	0.605
Effect of RESs	**Bus 9**	0.2	0.2	0.2	0.2
	Bus 12	0.332	0.95	0.95	0.95
	Bus 16	0.204	0.204	0.204	0.204
	Bus 19	0	0	0.2	0.4
	Bus 22	0.2	0.428	0.428	0.628
	Bus 25	0	0	0.2	0.2
	Bus 33	0	0	0.2	0.2
	Bus 35	0	0	0	0.41
Effect of AS	**Bus 12**	0	0.54	0.54	0.864
	Bus 22	1.204	1.204	1.204	1.204
Effect of DP	**Bus 12**	1.365	1.365	1.365	1.365
	Bus 16	0.2	0.2	0.2	0.2
	Bus 22	0.44	0.44	0.44	0.44
	Bus 33	0.2	0.2	0.2	0.2
	Bus 37	0.473	0.473	0.473	0.473
ESS (MWh)					
Effect of NEP	**Bus 2**	0	0	0	0.499
	Bus 12	0.502	1.039	1.513	1.995
	Bus 16	0.258	0.458	0.458	0.458
	Bus 22	0.2	0.492	0.692	0.692
	Bus 28	0	0	1.024	1.474
	Bus 33	0	0	0.2	0.2

	Bus 37	0.255	0.455	0.655	0.655
Effect of RESs	**Bus 9**	0.222	0.222	0.222	0.222
	Bus 12	0.366	0.98	0.98	0.98
	Bus 16	0.227	0.227	0.227	0.227
	Bus 19	0	0	0.2	0.4
	Bus 22	0.2	0.445	0.445	0.445
	Bus 25	0	0	0.2	0.4
	Bus 33	0	0	0.2	0.2
	Bus 35	0	0	0	0.41
Effect of AS	**Bus 12**	0	0.62	0.62	1.04
	Bus 22	1.41	1.41	1.41	1.41
Effect of DP	**Bus 12**	1.778	1.778	1.778	1.778
	Bus 16	0.2	0.2	0.2	0.2
	Bus 22	0.618	0.618	0.618	0.618
	Bus 33	0.2	0.2	0.2	0.2
	Bus 37	0.591	0.591	0.591	0.591

Vitae

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- Preparing and updating the corresponding progress schedule of the project of all sites.
- Preparing energization package.
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